ESSAYS ON THE EFFECTS OF VARIABLE DEBT OBLIGATIONS

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Peter Simasek

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ESSAYS ON THE EFFECTS OF VARIABLE DEBT OBLIGATIONS

Thesis committee:

Dr. Alex Hsu
Scheller College of Business
Georgia Institute of Technology

Dr. Andras Danis
Scheller College of Business
Georgia Institute of Technology

Dr. Robert Dittmar
Stephen M. Ross School of Business
Univerity of Michigan

Dr. Linghang Zeng
Finance Department
Babson College

Dr. Daniel Weagley
Scheller College of Business
Georgia Institute of Technology

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For my wife, Darcy

and my daughter, Siena

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SUMMARY

This dissertation consists of three essays on variable debt obligations. In the first essay, I develop a novel dataset to examine the impact of pension group annuity purchases on capital structure and corporate policies. Pension obligations are shown to contribute to rising cash flow volatility to stakeholders, which is a prominent factor in the decision to offload these liabilities. I find the reduction in pension debt is replaced with a commensurate dollar value of long-term debt. The substitution is concentrated in financially unconstrained firms, while those facing greater financial constraints reduce total leverage. Firms engaging in a group annuity purchase increase pension contributions and capital expenditures in the event year. Consistent with a lower expected probability of future cash shortfalls, changes to investment policy are concentrated in financially constrained firms. Short and long horizon event studies reveal pension annuity buyouts are associated with significantly negative abnormal returns due to disappointing cash flow news upon announcement.

In the second chapter of the dissertation, we exploit an exogenous, universal increase in discount rates mandated by the Moving Ahead for Progress Act (MAP-21) to identify the impact of pension overhang on investment. We find that firms with large unfunded pension liabilities increase investment by 13% after the MAP-21 induced decrease in pension liabilities. The effects are more pronounced for ex-ante financially constrained firms, yet pension-related cash flows have a minimal impact on investment. Credit ratings of affected firms improve while CEOs with more pay-forperformance and longer horizon increase investment to a greater extent after MAP-21. Our results highlight the role of pension overhang on investment.

In the third chapter, we examine the relative pricing of nominal Treasury bonds and Treasury inflation-protected securities (TIPS) in the presence of United States default risk. Higher bond yields are associated with a higher U.S. credit default swap premium, but more so for TIPS. This leads to a narrower breakeven inflation (BEI). An estimated no-

arbitrage model shows BEI is related to differing expectations of loss given default on the two Treasury securities and that most of the relative mispricing after the financial crisis can be attributed to default risk. Our finding suggests credit risk is embedded in the pricing of U.S. sovereign debt.

CHAPTER 1

PENSION RISK TRANSFER AND FIRM LEVERAGE: THE CASH FLOW VOLATILITY CHANNEL

1.1 Introduction

> *"We have substantially reduced the funding volatility associated with our pension plans while protecting benefits for retirees."* - Motorola Solutions CFO on $4.2 billion pension transfer

The past decade has witnessed a material and increasing volume of pension risk transfer events whereby the plan sponsor reduces or entirely offloads defined benefit (DB) pension obligations to a third party insurance company (pension buyout). The annual market extended to nearly $30 billion in 2019 from less than $1 billion in 2010.[1] Pension buyouts are costly and often cash intensive. While these transactions relieve the firm of associated future obligations to beneficiaries, the premium paid in the form of cash and marketable securities virtually always exceeds the present value of the pension obligation. Furthermore, the firm forfeits a tool to manage future tax payments, negotiating leverage with its workforce,[2] and the put option value derived from Pension Benefit Guarantee Corporation (PBGC) backing. Are there unique features of the pension liability that have made this form of debt financing increasingly less desirable? How might pension buyouts impact capital structure, firm operations, and shareholder returns?

A possible motivation for pension buyouts lies in the desire to manage cash flow risks. Firms have ample tools at their disposal to minimize exposure to numerous firm-specific and macroeconomic factors that introduce volatility. Under many circumstances, the size and nature of risk can be accurately determined and hedged through derivative contracts.

[1]Based on Legal & General Pension Risk Transfer Monitor
[2][1]; [2]

The literature has provided extensive evidence that firms actively engage in these hedging activities to smooth earnings, avoid costs of financial distress, and limit needs for costly external finance ([3]; [4]; [5]; [6]). Amid imperfect markets, certain cash flow risks remain without comparable hedging instruments or where the cost may surpass the benefit. The DB pension obligation may be one of the largest such risks to a sponsoring firm with numerous, time-varying inputs impacting the demand on firm cash flows.[3] An alternative risk management strategy, aside from hedging, is to remove the source of risk.

This paper seeks to address the role of cash flow volatility with respect to defined benefit pension obligations and corporate capital structure. I construct a unique dataset from hand-collected information on pension risk transfer events and plan-level premium data gathered from a FOIA request to the PBGC. I combine these data with pension plan filings from Internal Revenue Service (IRS) Form 5500 and company financials to investigate the role of pension obligations as a contributor to increasing cash flow volatility. Firms with higher ex ante cash flow volatility have been shown to avoid adoption of a DB pension plan when first initiating a retirement scheme [7]. Conditional on sponsoring a DB plan, I find the probability of a firm engaging in a pension buyout is significantly related to rising volatility.

In the year immediately following a buyout transaction, firms substitute for a more predictable funding source (long-term debt) and the degree of financing is commensurate with the size of prior pension relief. Frictions arising from financial constraints suggest a differential response in the cross-section of buyout firms. Offloading pension obligations lowers future cash flow volatility, yet may also serve as a mechanism to reduce total leverage. [8] highlight the significance of cash flow sensitivity to constrained firms while unconstrained firms should be able to fund investment projects with unrestricted access to external financing. Notably, the substitution of volatile pension liabilities for long-term debt is concentrated in financially unconstrained firms. Using several measures, I observe less financially constrained firms change the composition of their consolidated balance sheets while those

[3]Pension oligations amount to approximately 14% of firm assets in the sample. In the U.S., total assets in private defined benefit pension plans exceed $2.5 trillion

experiencing greater constraints reduce total leverage.

The literature has primarily focused on the *level* of pension debt and cash contributions with respect to corporate capital structure ([9]; [10]). These authors measure a substitution rate of approximately 25-35% of long-term debt relative to pension obligations based on the respective existing degree of leverage in a consolidated capital structure. Buyout transactions provide a distinct setting to study the *changes* in the composition of debt. In the context of pension risk transfer events, I document rates of substitution that are at least twice as large as has been previously reported.

Unique features of the pension obligation differentiate it from traditional forms of debt financing. Specific market, regulatory, and demographic factors, which are generally outside managerial control, introduce time-varying volatility into the magnitude of the pension obligation and mandatory annual cash flows. Additionally, the collateral backing the liability is a portfolio of market securities which has a direct effect on the cost of capital ([11]). The decision to offload pension liabilities may then have various implications with respect to firm operations stemming from a reduction in the potential for future cash shortfalls. In the event year, firms increase cash contributions to the pension plan to fully fund the buyout transaction and maintain plan funded status. Evidence from [12] and [13] suggests mandatory pension contributions inhibit discretionary investment such as capital expenditures and R&D. Despite higher pension contributions, and after controlling for investment related factors (including cash flows), I find firms also increase capital expenditures in the year they engage in a buyout. The effect is most pronounced for financially constrained firms, consistent with lower expected cash flow volatility ([14]).

I further investigate the impact of pension risk transfer events on shareholder returns. Theory would suggest a reduction in systematic risk from the pension obligation should increase value to shareholders. However, there are also significant cash flow implications to fully fund the group annuity premium, which may induce a negative market reaction ([15]). It then becomes an empirical question whether risk mitigation or negative cash flow news is the dominant factor for market participants. In both short and long horizon event studies I find firms engaging in a pension risk transfer experience negative abnormal returns. Leveraging the return decomposition of [16], I decompose quarterly returns into cash flow and discount rate news components. The expected return news component experiences minimal change while negative cash flow news dominates in the quarter the buyout is announced. While managers may prefer a reduction in funding volatility from the pension, shareholders appear to place greater weight on the realization of the cash demands.

This study makes several contributions to our understanding of firm risk and the role of pension liabilities in corporate capital structure. To my knowledge, this is the first paper to empirically examine the effects of the growing U.S. pension risk transfer market on corporate policies. Offloading pension liabilities through a group annuity purchase has important implications for corporate capital structure, investment, and firm value. The number and magnitude of pension risk transfer transactions are expected to continue their recent upward trend.[4]

The paper proceeds with Section section 1.2 describing relevant features of defined benefit pension plans and how recent factors may impact funding volatility over the sample period. Section section 1.3 provides institutional details regarding pension de-risking strategies. A description of the data and empirical results related to capital structure and investment policy are presented in Section section 1.4. Section section 1.5 documents the impact on returns and Section section 1.6 concludes.

1.2 Defined benefit plans and rising volatility

Defined benefit (DB) pension plans provide an annuity to former employees in retirement in exchange for lower wages in their working years. It creates a long term liability with features closely resembling financial debt, yet only a portion is reflected on the balance sheet. The value of the annuity is generally a function of several factors including years of

[4]Metlife 2019 Pension Risk Transfer Poll

service and final wage incentivizing commitment to, and growth within the firm. Pension beneficiaries are then creditors to the firm in a true economic sense ([17]). Each year, under strict regulations outlined by Congress, the firm is required to make cash contributions toward the present value of underfunded pension liabilities. Failure to meet mandatory contributions can lead to bankruptcy while the PBGC is often one of the largest creditors in these cases.[5]

Pension liabilities differ from long-term debt in unique aspects that introduce considerable volatility beyond what would be expected from cash flows to external creditors. The most prominent risks facing the pension arise from plan investments, worker longevity, and changes to the pension regulatory environment. These factors affect the funded status of the plan and as a result, required contributions, are generally out of the control of the plan sponsor and difficult to fully hedge. Pension contributions are typically invested in a diversified portfolio of marketable securities. At a given time, pension assets are then the cumulative sum of all prior contributions plus the gains (losses) from returns on the portfolio. The firm is responsible for future payments to employees and is subject to the associated risks of any funding shortfalls, which can be substantial. Prior to the financial crisis in the spring of 2008, the average large corporate DB plan maintained a funded ratio of more than 100% (pension assets greater than present value of liabilities). Due to a collapse in asset prices and lower interest rates spurred by monetary policy, the average funded status fell to 75% in early 2009. A $250 billion dollar pension funding shortfall among the largest plan sponsors arose in less than twelve months.[6]

Under the construct of a typical DB plan, the firm bears virtually all risk. This contrasts with a defined contribution (DC) pension plan which does not create a long-term liability for the firm. The individual worker is responsible for management of her own retirement portfolio and must account for personal longevity risk. As part of a DC pension scheme,

[5] See [18] and [19] for further discussion of pension plans in bankruptcy. Recently, the in the well-publicized bankruptcy of Sears Holdings Corp., the PBGC was the largest single unsecured creditor.

[6] Milliman Pension Funding Index

workers have the option, but not the requirement, to fund their personal account. Most sponsors offer matching contributions up to certain thresholds, yet maintain the flexibility to reduce or suspend these contributions at any time. The decision to reduce retirement benefits in DC plans was prevalent in the aftermath of the global financial crisis.[7] DC pension plans result in lower operating leverage and total firm leverage. The analysis in this paper is then relevant only to firms sponsoring DB pension plans.

1.2.1 Changes affecting pension contribution volatility

Over the sample period of 2010-2019, numerous changes (both regulatory and market-related) across the pension landscape added to funding volatility. In a recent industry survey of DB pension plan sponsors, the top financial priority was to minimize volatility in contributions and funding ratio.[8] Furthermore, leading drivers for sponsors to make changes to the plan include reducing costs and cost volatility. Notably, the dramatic rise in pension risk transfer events coincides with the implementation of many of these factors affecting plan volatility. I describe in Section section 1.3 why pension buyouts are the most effective tool to address these concerns.

PBGC premiums

The Pension Benefit Guaranty Corporation was established in 1974 as part of broad legislation to regulate corporate defined benefit pension plans in the U.S. The PBGC functions as an insurance provider should a sponsor firm enter bankruptcy and find itself unable to fund plan liabilities. Under these circumstances, the PBGC will assume the liability, existing assets, and maintains a claim on the firm for the unfunded portion of liabilities. The PBGC is funded through annual premiums levied on pension plan sponsors. In 2010, premiums were approximately 8% of benefit accruals in a given year for a firm in the sample. This figure more than tripled to over 25% of annual accrued benefits at the end of the

[7] See http://www.pensionrights.org/publications/fact-sheet/companies-have-changed-or-temporarily-suspended-their-401k-matching-contribu

[8] Vanguard 2019 Survey of Pension Sponsors

sample. There are two components to annual premiums - a fixed and variable rate premium. Fixed rate premiums are based on the number of employees covered by the plan and have doubled since 2010. The variable rate premium is based on the degree of underfunding. Variable rate premiums have risen from less than 1% of the unfunded liability to 4.3% in 2019. These premiums are not directly based on the likelihood of the PBGC having to assume the liabilities of a given sponsor suggesting they are almost certainly mispriced. Higher premiums may incentivize financially stronger firms to offload liabilities as they are subsidizing costs for weaker firms. The sample of firms engaging in a pension buyout are on average larger, have higher market-to-book ratios, and are more profitable relative to their non-annuity peers.

Updates to mortality tables

The IRS publishes mortality tables to be used in the calculation of DB plan obligations. The tables are based on the guidance provided by the Society of Actuaries (SOA). Survivorship figures were updated in 2014 from prior tables released in 2000. The new mortality tables reflected increases in life expectancy, which the SOA estimates would increase private pension liabilities by 4-8%. The decline in mortality rates had the largest effect on older segments of the population effectively raising the duration of plan liabilities. Naturally, the demographics of plan beneficiaries may lead to heterogeneous outcomes for plan liabilities, funded status, and mandatory contributions.

Legislative initiatives

Beginning with the Moving Ahead for Progress in the 21st Century Act (MAP-21), several bills have enacted changes to pension discount rates and PBGC premiums. In 2012, in attempts to offset costs associated with transportation funding, MAP-21 instituted higher discount rates to calculate pension liabilities. The higher rates reduced the size of pension obligations in attempts to reduce tax-deductible pension contributions and effectively raise corporate tax revenue. Subsequent legislation in the form of the Bipartisan Budget Acts of 2013 and 2015, as well as the Highway Transportation and Funding Act of 2014 (HATFA) extended the usage of higher discount rates imposed by MAP-21 and introduced the increases in PBGC premiums discussed previously. Each of these acts involved a timeline in which the discount rate impact was intended to be phased out over time. A reversion to lower discount rates (higher pension obligation) is currently scheduled to begin in 2021. The legislation likely provided temporary relief in terms of the size of pension liabilities and mandatory contributions [20]. However, the constant changes in funding rules would also be expected to raise administrative costs and manager uncertainty.

Monetary policy - rising interest rates

The first half of the sample is defined by a period of loose monetary policy when the Federal Reserve held the fed funds rate near the zero lower bound until late 2015. The latter part of the sample, where I witness a rise in pension risk transfer events, is encompassed by tighter monetary policy and increases to the fed funds rate. The 10-year Treasury yield traded in a range from 1.3% to as high as 4% throughout the sample. Pension obligations are discounted according to IRS supplied rates that are based on either historical government bond yields or an index of high grade corporate bonds (depending on timing of the legislative items discussed). Given the long duration nature and material size of pension obligations relative to the consolidated firm balance sheet, changes to discount rates can have a significant impact on the value of pension liabilities.

These matters encompass the most notable changes to the pension landscape, while other, more difficult to quantify factors may also have a critical role in pension funding policy. Greater manager attention may need to be dedicated to the unfunded pension liabilities and away from operations. Additionally, expertise in directing a sizable pension portfolio likely differs across firms. Collectively, these issues have increased the complexity of managing DB pension obligations.

1.3 Pension Risk Transfer

This paper highlights the impact of pension risk management through the purchase of a group annuity from a third party insurance company. Firms often purchase the annuities for a subset of plan participants, yet in several cases, usually associated with plan terminations, the buyouts can cover the entire remaining pension obligation. The transaction fully and irrevocably relieves the plan sponsor of future obligations to associated beneficiaries and is funded with a combination of cash and plan assets. They are not limited to certain timing or plan demographics. In terms of dollar value of liabilities and the ability to remove the entirety of associated risk, insurance transactions represent the most economically material action a plan sponsor can undertake.

Nonetheless, other methods to de-risk pension obligations have seen increasing utilization. Firms seeking to reduce pension volatility likely employ multiple strategies. Since the early 2000s, there has been a consistent trend of freezing the plan to new entrants and halting accruals to existing participants. [21] examine these events arguing firms experience an increase in risk in the quarters after a plan freeze due to a reduction in inside debt. Some plans have pursued immunization strategies in which they alter pension asset allocation. This approach may include hedging instruments to manage downside risk or, more often, a shift toward long-duration fixed income with the intent of matching cash flows of pension assets and liabilities. Lastly, a firm may offer existing participants a lumpsum equivalent to the present value of their future benefits. The former plan participant then bears all future investment and cash flow risk. Similar to an insurance transaction, lumpsum offerings permanently remove associated pension obligations for the firm.

Each of these methods have numerous shortfalls relative to the ability to reduce risk through purchasing a group annuity contract. Freezing the plan either reduces or halts future accruals, but does not reduce existing liabilities. Although changing the asset allocation may reduce capital market risk, it is virtually impossible to fully inoculate the plan as precise duration matching would require frequent rebalancing. Additionally, the prior two strategies do not reduce ongoing administrative costs, PBGC premiums, or address longevity risk inherent in defined benefit pension plans. Lumpsum payouts address several of these concerns, yet are governed by specific IRS regulation that has limited their expanse. Their use is further limited by employee demographics. During much of the sample period, the ability to offer lumpsums to retiree beneficiaries was limited and they cannot be offered to active employees accruing benefits. Lumpsums are generally targeted at a subset of former employees not yet receiving benefits. The choice to accept a payout lies with the plan participant introducing moral hazard implications into this de-risking strategy. Information on participant health is largely asymmetric. Participants expecting a long lifespan would be less likely to accept a lumpsum while those that unfortunately face health struggles may opt in potentially receiving a greater net benefit. Due to these considerations, a firm seeking to most effectively reduce pension risk would be expected to rely on a group annuity contract.

1.4 Empirical Analysis

1.4.1 Data

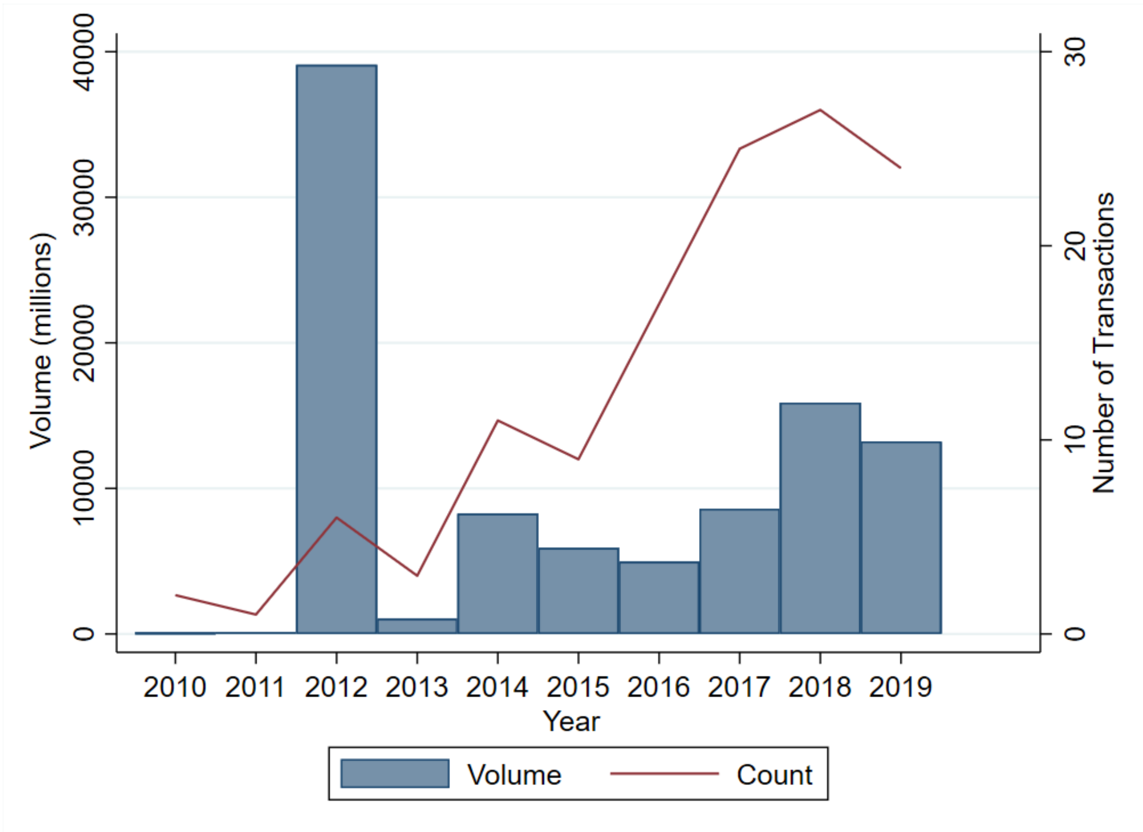
I utilize a variety of sources to construct a novel dataset of pension risk transfer events from 2010-2019. I collect information on insurance group annuity and lumpsum transactions from web scraping SEC filings, reviewing IRS Form 5500 filings and associated schedules, and searching related news articles. Information on PBGC premiums was obtained through a FOIA request. Schedule R of Form 5500 requires plan sponsors to report the number of participants whose benefits were distributed in a single lumpsum for a given year. Schedule H of Form 5500 includes line items for distributions to insurance carriers as well as “Other” plan distributions above and beyond the scheduled benefit payments to retired beneficiaries. Although the majority of events are accurately represented in these documents, there are many cases where the data must be attained from the qualitative discussion in filings or press releases. To my knowledge, a standardized reporting format for the announcement or recording of specific pension risk transfer events does not currently exist. Each transaction therefore is verified by discussion in an SEC filing, news article, or press release. The unique firm identifier for Form 5500 filings is the sponsor's employer identification number (EIN). In many instances, the sponsor of the defined benefit pension plan is a subsidiary of the consolidated parent company appearing in the Compustat database. To ensure I capture all U.S. plans for which the parent company is obligated, I hand match wholly owned subsidiaries from 10-K filings with sponsor names from Form 5500 filings and consolidate these to the parent company level. The final sample includes 132 transactions with buyouts averaging approximately $750 million (median $157 million). Figure 1.1 displays the volume and number of buyout transactions by year. The outsized volume in 2012 can be attributed primarily to one large transaction from General Motors.

The remaining data in my sample are sourced from Compustat and CRSP. The analysis in this paper primarily relies on Compustat pension data. In order to examine the consolidated leverage of a firm both domestic and foreign pension obligations are required. The Form 5500 filings are only required for domestic defined benefit plans. For firms I am able to match to the Form 5500 data, total U.S. pension liabilities account for over 80% of liabilities reported in SEC filings. Differences in the calculation of the liabilities between the two data sources, foreign pension plans, and plans I am unable to match to the parent company account for the difference. The two calculations have a correlation of 0.94 in my sample. With the introduction of FASB 158 in 2006, firms are required to report the net pension deficit on the balance sheet. I adjust firm level variables to prevent double counting of pension-related variables on the consolidated balance sheet.

Table 1.1 reports descriptive statistics for the Compustat (Panel 1) and Form 5500 (Panel 2) data used in the empirical analysis. The data consists of firm-year observations split between sections A and B to separate the firms that ultimately engage in an insurance

Figure 1.1: Insurance Transactions

This figure shows the volume and number of pension buyout transactions in the sample. The outsized volume in 2012 can be attributed primarily to one large transaction from General Motors.



transaction during the sample period. Notably, the firms which engage in group annuity transactions are generally larger and have a significantly higher level of pension debt in their consolidated capital structure (21% of consolidated assets compared to 13% for non-annuity firms). The firms choosing a group annuity are characterized by higher market-to-book ratios and increasing standard deviation of cash flows. Form 5500 data suggests annuity firms experience a moderately higher funded status, have a greater percentage of retired plan participants and opt for an asset allocation weighted toward investment grade debt. A higher debt allocation (relative to equity, high yield, or alternative assets) suggests the annuity firms further lean toward de-risking through more closely matching the duration of assets to liabilities.

Table 1.1: **Summary Statistics**

Table 1.1 provides summary statistics for firm-year observations from 2010-2019 for companies sponsoring a defined benefit pension plan. Panel 1 provides details on firm level variables provided by Compustat. Panel 2 provides details on specific pension plan characteristics unique to Form 5500 filings. Total assets and revenue are in dollars millions. The designation “BS” refers to balance sheet assets while “Cons” is the sum of balance sheet and pension assets. $LT\ Debt$ is financial debt appearing on the balance sheet. $Pen\ Debt$ is the pension liability based on the projected benefit obligation (PBO). $Pen\ Deficit$ represents the underfunded status of the pension plan (liabilities less assets) while $TotDebt$ combines balance sheet debt with pension liabilities. MTB is the market value of equity, less book value of equity, plus balance sheet assets divided by balance sheet assets. ROA is defined as net income divided by balance sheet assets. $Collateral$ is net property plant and equipment. $Cash\ Flow\ Pension$ represents free cash flow to external stakeholders. I define as total revenue minus cost of goods sold, SG&A, change in working capital, pension contributions, and taxes paid. $CFP\ SD\ Ratio$ represents the prior 10-year standard deviation of $Cash\ Flow\ Pension$ scaled by the average standard deviation in the sample. $FundedStatus$ is the weighted average plan funded status from Form 5500 filings. $Discount\ Rate$ reflects the effective discount rate used to calculate pension liabilities. Percent $Active$, $Separated$, $Retired$ refer to the demographics of plan participants. $Equity$ and $InvGrade$ represent weighted portfolio allocations of firm plans. Var and FR represent the variable and flat rate annual pension premiums scaled by the normal cost.

Panel 1	(1A Non-Annuity Firm, Compustat Variables)						(1B - Annuity Firm, Compustat Variables)					
	Mean	p10	Median	p90	St. Dev	Observations	Mean	p10	Median	p90	St. Dev	Observations
Total Assets	10728	271	2501	22025	34429	7560	17049	913	4924	36787	36623	1030
Revenue	7627	252	2075	16333	20610	7560	16511	978	4772	36823	33721	1030
LT Debt / BS Assets	0.27	0.01	0.25	0.53	0.22	7560	0.25	0.07	0.24	0.43	0.15	1030
LT Debt / Cons Assets	0.25	0.01	0.22	0.49	0.20	7560	0.20	0.05	0.20	0.35	0.13	1030
Pen Debt / Cons Assets	0.13	0.01	0.08	0.30	0.15	7560	0.21	0.03	0.18	0.43	0.16	1030
Pen Deficit / Cons Assets	0.03	0.00	0.02	0.07	0.09	7560	0.04	0.00	0.02	0.10	0.04	1030
Tot Debt / Cons Assets	0.41	0.11	0.38	0.66	0.89	7560	0.43	0.20	0.42	0.65	0.18	1030
Cash / BS Assets	0.11	0.01	0.08	0.25	0.11	7560	0.11	0.02	0.08	0.25	0.10	1030
CapEx / BS Assets	0.04	0.01	0.03	0.08	0.04	7560	0.04	0.01	0.03	0.07	0.03	1030
Collateral / BS Assets	0.26	0.06	0.20	0.60	0.21	7560	0.25	0.06	0.22	0.48	0.17	1030
MTB	1.76	0.98	1.47	2.70	1.53	7560	1.93	1.09	1.63	3.12	1.06	1030
ROA	0.03	-0.06	0.04	0.11	0.27	7560	0.06	-0.00	0.05	0.13	0.07	1030
Cash Flow Pension	0.09	0.01	0.10	0.18	0.14	7560	0.11	0.04	0.10	0.18	0.08	1030
CFP Vol Ratio	1.01	0.65	1.01	1.35	0.32	7560	1.20	0.69	1.00	1.58	1.18	1030

Panel 2	(2A - Non-Annuity Firm, Form 5500)						(2B - Annuity Firm, Form 5500)					
	Mean	p10	Median	p90	St. Dev	Observations	Mean	p10	Median	p90	St. Dev	Observations
Funded Status	96.80	80.00	96.15	113.41	16.73	3958	98.38	80.03	97.85	114.26	19.19	901
Discount Rate	6.44	5.69	6.28	6.91	10.55	3958	6.27	5.73	6.28	6.85	0.46	901
Percent Active	0.34	0.10	0.31	0.61	0.20	3958	0.29	0.09	0.27	0.55	0.18	901
Percent Separated	0.31	0.15	0.29	0.49	0.13	3958	0.32	0.17	0.30	0.48	0.13	901
Percent Retired	0.36	0.10	0.36	0.60	0.18	3958	0.39	0.14	0.39	0.63	0.19	901
Equity	38.21	0.00	44.00	68.00	25.89	3958	38.98	0.00	42.00	66.00	22.53	901
Inv Grade	26.02	0.00	26.00	53.57	21.13	3958	36.96	0.70	33.97	70.70	23.07	901
Var Premium / Normal Cost	0.20	0.00	0.06	0.58	0.30	3880	0.16	0.00	0.05	0.53	0.22	894
FR Premium / Normal Cost	1.17	0.01	0.07	0.29	51.43	3880	0.14	0.02	0.08	0.27	0.34	894

1.4.2 Cash flow volatility and pension liabilities

Engaging in a pension buyout through a group annuity contract is costly. The premium, relative to existing pension obligations, has averaged approximately 105% over the past decade.[9] The firm must then either have a substantially overfunded pension plan or must make additional cash contributions to fund the buyout. Furthermore, there are administrative costs associated with selecting the benefits to offload, organizing demographic data, and making changes to existing asset allocations. The portfolio composition of the pension plan would not be expected to perfectly mirror the allocation of the insurance company's general fund. Trading costs may then be added to group annuity premiums for in-kind transactions.

The value maximizing manager must then believe these costs are more than offset through alternative channels. In this section, I explore one potential channel - rising cash flow volatility. A wide body of literature has explored the extent of corporate risk management and the potential value it creates for stakeholders.[10] In the case of the pension liability, the inherent risks are difficult to fully hedge. Partial or entire removal of the pension obligation may then prove a prudent risk management strategy. Although I show the pension liability contributes to increasing cash volatility, the analysis does not claim it is necessary that the incremental cash flow volatility is solely driven by pension funding policy. Rather, firms experiencing higher cash flow volatility from operations would also be expected to consider a reduction in pension volatility if this was the most cost effective solution in the context of a broader enterprise risk management strategy [22].

Prior to the last decade, pension buyouts through group annuities were rare except in the case of plan terminations. Under a termination, the defined benefit plan is closed and current employees are enrolled in a new defined benefit plan or a defined contribution plan.

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[9] See Milliman Pension Buyout Index: https://www.milliman.com/en/insight/milliman-pension-buyout-index-july-2020

[10] [6] show that convex cost structures incentivize hedging. Furthermore, hedging is shown to add value in the case of costly external finance [5]. [14] empirically investigate how cash flow volatility is associated with firms forgoing investment and leads to higher costs of external finance.

Previous work has shown that terminations and reversions occurring in the 1980s resulted from high levels of overfunding following strong equity returns and high interest rates. Firms most likely to face financial constraints were associated with a higher probability of terminating a pension plan [23] [24]; [25]; [26]. These transactions differ from the annuity buyouts witnessed more recently. Firms are generally underfunded during my sample period and I find pension contributions actually increase in the event year in order to offload the liability. Stricter tax implications have also since been enacted making reversions less attractive.

I use the standard deviation of cash flows to stakeholders over the prior 10 years to measure cash flow volatility. Specifically, I seek to capture rising cash flow volatility. [7] cites cash flow volatility as a key reason a firm may not originally adopt a defined benefit pension plan. By nature of the topic, the sample is limited to firms sponsoring already sponsoring a defined benefit plan. It follows that the choice to offload the pension may be associated with changes in levels or volatility of pension funding. I capture changes in cash volatility through the Cash Flow (Pension) Volatility Ratio defined as:

$$CFP\ Vol\ Ratio_{i,t} = \frac{\sigma_{i,t}}{\overline{\sigma_i}} \tag{1.1}$$

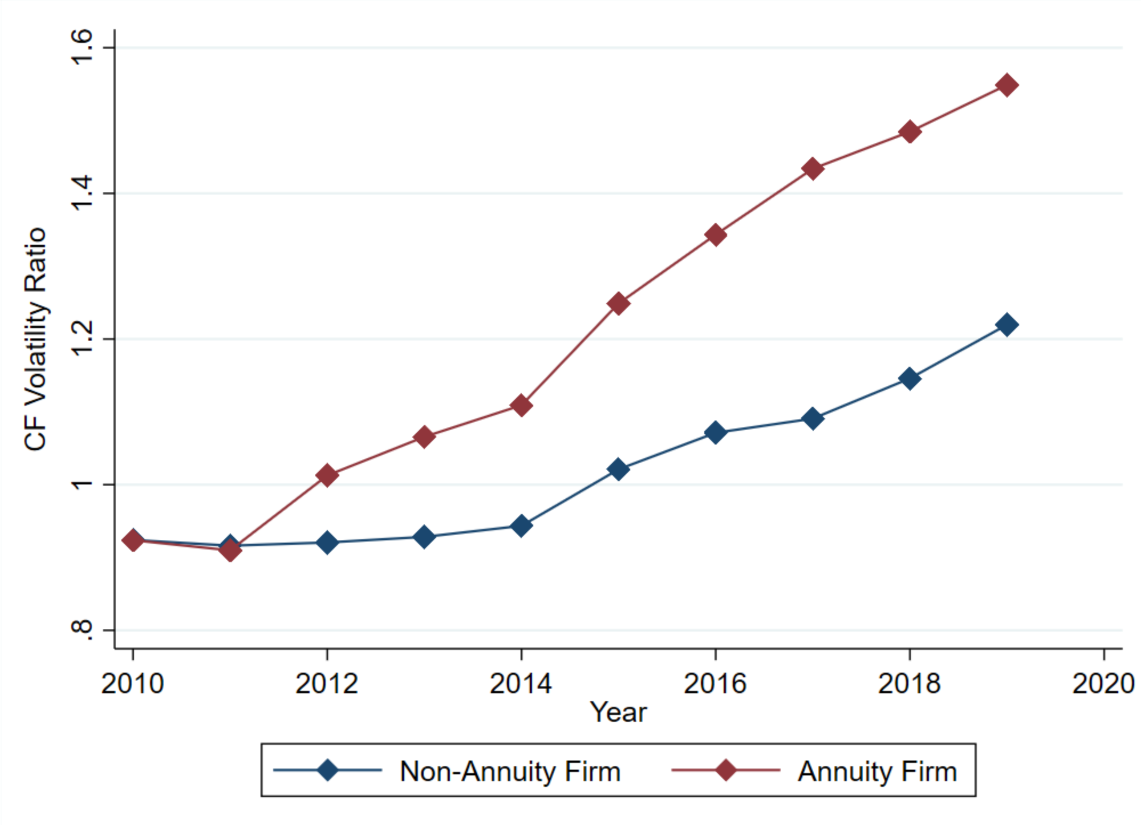
The numerator represents the prior 10 year standard deviation of cash flows for each firm-year while the denominator is the average cash flow volatility over the sample period. I define cash flows as total revenue less cost of goods sold, SG&A, changes in working capital, pension contributions, and taxes paid. The figure then represents cash flow available to external creditors and shareholders. I truncate the denominator to the years prior to the first group annuity transaction for an event firm to ensure changes in volatility ex post are not driving the results. Figure 1.2 shows the evolution of the volatility ratio. While all firms in the sample experience increases in cash flow volatility, those which ultimately engage in pension buyout activity see outsized effects.

In Table 1.2, I examine the factors driving the volatility ratio in a pooled fixed effects

Figure 1.2: Evolution of Cash Flow Volatility Ratio

The figure shows the average CFP volatility ratio throughout the sample period of 2010-2019. Cash flow is defined as total revenue less cost of goods sold, SG&A, changes in working capital, pension contributions, and taxes paid. The CFP volatility ratio is:

$$CFP\ Vol\ Ratio_{i,t} = \frac{\sigma_{i,t}}{\overline{\sigma_i}} \tag{1.2}$$



regression model. The dependent variable in columns (1)-(4) is described by equation (1). Notably, the size of the pension obligation scaled by consolidated assets is significant across all specifications. The pension liability appears to be introducing additional volatility to cash flows to stakeholders. In column (4), I include both firm and industry-by-year fixed effects to ensure unobserved industry trends are not driving operational volatility which would appear in the measure selected. The coefficient of interest is actually larger. A one standard deviation increase in the pension liability implies an approximate 8-10% increase in the volatility measure. Columns (2)-(4) include the PBGC premium and Form 5500 level data. With shorter horizons and determined annuity payments, a higher percent of retired participants reduces volatility while total PBGC premiums are a source of volatility for plan sponsors. I exclude the impact of pension contributions and taxes in the cash flow volatility measure in column (5). I find no significant relation between the size of the pension liability or pension deficit with this measure of cash flow volatility.

Adding the pension deficit (level of underfunding) in columns (3)-(5) does not appear to have an impact on volatility outside of the variation explained by the total obligation. This is a notable given the debate in the literature on which measure of pension debt matters - the total liability or the underfunded portion. The remaining controls enter with the expected signs. Higher market-to-book firms are generally characterized as having greater growth opportunities, which would be expected to carry higher risk. Larger firms, represented by the log of total assets, are less financially constrained with the ability to easily access external sources of funding. Facing fewer market frictions, larger firms could support more volatile cash flows. Higher cash holdings have been shown to be a sign of precautionary saving and would be correlated with higher cash flow volatility.

Results from Table 1.2 suggest the size of the pension liability plays a central role in explaining rising cash flow volatility. To examine the importance of the volatility ratio in the context of pension risk transfer, I turn to a probit model in Table 1.3. I test whether a series of firm and pension variables are predictive of a firm offloading pension liabilities. The dependent variable is equal to one for any firm-years where I can identify a pension buyout transaction and zero otherwise. Column (1) includes financial variables while columns (2) and (3) further incorporate Form 5500 pension variables and the asset allocation, respectively. The control variables, are lagged one period with the exception of the volatility measure. Higher volatility in the event year may incentivize the timing of the risk transfer event. In further tests to ensure the event is not driving the volatility, I also lag the CFP Vol Ratio and economic as well as statistical significance are essentially unchanged. Both the cash flow volatility ratio and the size of the pension obligation relative to consolidated assets are highly significant across specifications. Larger firms (assets) and those with greater

Table 1.2: **Cash Volatility of Pension Firms**

Table 1.2 presents results from a fixed-effects regression model of the cash flow volatility measure on total pension liabilities and a series of financial and pension-specific control variables. The dependent variable in columns (1)-(4) is the CFP Volatility Ratio described in equation (1). The dependent variable in column (5) is constructed identically with the exception of removing pension contributions and taxes from the cash flow calculation. $Cons\ Assets$ represents the consolidated firm assets - the sum of balance sheet and pension assets according to Compustat data. $Pen\ Debt$ is the total value of the pension obligation. $Pen\ Deficit$ represents the underfunded status of the pension plan (liabilities less assets). $LT\ Debt$ is the size of long-term debt from the balance sheet. MTB is the log of market value of equity, less book value of equity, plus balance sheet assets divided by balance sheet assets. $Total\ Assets$ is the log of balance sheet assets. ROA is defined as net income divided by balance sheet assets. $Discount\ Rate$ reflects the effective discount rate used to calculate pension liabilities. Percent $Active,\ Retired$ refer to the demographics of plan participants. $Premium/Norm\ Cost$ is the total annual pension premiums scaled by the normal cost. I include firm and year or firm and industry-by-year fixed effects in each specification. Standard errors are clustered at the firm-level.

	(1) CFP Vol	(2) CFP Vol	(3) CFP Vol	(4) CFP Vol	(5) OP CF Vol
$Pen\ Debt/Cons\ Assets$	0.520***	0.590**	0.668**	0.750**	0.453
	(2.62)	(2.16)	(1.98)	(2.10)	(1.38)
$Pen\ Deficit/Cons\ Assets$			-0.238	-0.387	0.134
			(-0.41)	(-0.64)	(0.20)
$LT\ Debt/Cons\ Assets$	-0.046	-0.108	-0.106	-0.127	-0.134
	(-0.55)	(-0.92)	(-0.89)	(-1.09)	(-1.45)
MTB	0.083**	0.112*	0.111*	0.147**	0.088**
	(2.15)	(1.94)	(1.96)	(1.99)	(2.06)
$Total\ Assets$	0.421***	0.432***	0.434***	0.468***	0.436***
	(9.67)	(5.17)	(5.26)	(4.97)	(8.13)
$Cash/Cons\ Assets$	0.167	0.351**	0.354**	0.335*	0.157
	(1.54)	(2.05)	(2.06)	(1.67)	(1.45)
ROA	-0.209***	-0.163**	-0.166***	-0.113*	-0.210***
	(-4.22)	(-2.53)	(-2.63)	(-1.86)	(-4.05)
$Discount\ Rate$		-0.000	-0.000	-0.000	
		(-0.71)	(-0.83)	(-1.40)	
$Pct\ Retired$		-1.078*	-1.080*	-1.095*	
		(-1.86)	(-1.86)	(-1.69)	
$Pct\ Active$		-0.281	-0.276	-0.141	
		(-1.14)	(-1.10)	(-0.54)	
$Premium/Norm\ Cost$		0.001***	0.001***	0.001**	
		(5.64)	(4.49)	(2.17)	
N	8317.000	4588.000	4588.000	4587.000	8317.000
R-squared	0.571	0.630	0.630	0.661	0.540
Firm	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	No	No
Industry	No	No	No	No	No
IndustryxYear	No	No	No	Yes	Yes

t statistics in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

investment opportunities (MTB) show a higher probability of purchasing a group annuity. The relative size of long-term debt to the consolidated balance sheet does not appear to play a role in predicting pension buyouts. It follows that reducing total leverage is not expected to be a primary motivation for most firms.

The significance of several pension-related variables bear further discussion in the context of an annuity buyout. Pension sponsors with a greater percent of retired participants are considerably more likely to seek out these transactions. The premium charged by insurance companies will take into consideration the uncertainty embedded in future payouts. Benefits to existing retirees have shorter horizons relative to active workers and the final annual benefit, which is often a function of final wages and years worked, has already been determined. A higher investment grade debt allocation signifies these firms have already began de-risking the pension liability through a tilt toward an LDI strategy. Debt holdings would also be consistent with a strategy of the firm aligning the pension asset allocation to more closely resemble that of the insurance company. This will reduce trading costs in an in-kind transfer of assets. Lastly, the effective discount rate appears in the regression with a negative sign. The IRS determines the discount rates used for pension plans based on three segment rates. The segments rates are based on the timing of benefit distributions and are divided into periods of zero-to-five years, five-to-twenty years, and greater than twenty years. Given and upward sloping yield curve, a younger workforce would then be associated with a higher effective discount rate. Consistent with the previous discussion on retirees it holds that pension plans encompassing a younger demographic would face a higher cost to annuitize. Even after the consideration of pension demographics and asset allocation, I find the probability of a pension buyout is significantly related to cash flow volatility and the coefficient shows minimal change across specifications.

Table 1.3: **Determinants of Pension Risk Transfer**

Table 1.3 presents results from a probit model estimating the choice to pursue a pension buyout. $Insurance$ is equal to 1 for all firm-year observations in which the firm engages in a pension risk transfer event. Financial and pension variables are lagged by one year. $CFP\ Vol\ Ratio$ is defined as in equation (1). $Cons\ Assets$ represents the consolidated firm assets - the sum of balance sheet and pension assets according to Compustat data. $Pen\ Debt$ is the total value of the pension obligation. $Pen\ Deficit$ represents the underfunded status of the pension plan (liabilities less assets). $LT\ Debt$ is the size of long-term debt from the balance sheet. MTB is the log of market value of equity, less book value of equity, plus balance sheet assets divided by balance sheet assets. $Total\ Assets$ is the log of balance sheet assets. ROA is defined as net income divided by balance sheet assets. $Discount\ Rate$ reflects the effective discount rate used to calculate pension liabilities. Percent $Active,\ Retired$ refer to the demographics of plan participants. $Premium/Norm\ Cost$ is the total annual pension premiums scaled by the normal cost. $Pct\ Stock$ and $Pct\ InvGrade$ refer to the asset allocation of plan assets. Standard errors are clustered at the firm-level.

	(1) Insurance	(2) Insurance	(3) Insurance
$CFP\ Vol\ Ratio$	0.175***	0.198***	0.182***
	(2.96)	(3.68)	(3.29)
$Pen\ Debt/Cons\ Assets$	2.431***	1.593***	1.550***
	(6.44)	(2.92)	(2.91)
$Pen\ Deficit/Cons\ Assets$	-5.191***	-3.069	-2.935
	(-3.26)	(-1.51)	(-1.42)
$LT\ Debt/Cons\ Assets$	-0.082	0.049	0.021
	(-0.40)	(0.14)	(0.06)
MTB	0.250***	0.262*	0.242*
	(2.68)	(1.96)	(1.79)
$Total\ Assets$	0.093***	0.110***	0.095***
	(4.33)	(3.40)	(2.65)
$Cash/Cons\ Assets$	-0.070	0.745	0.795
	(-0.14)	(0.92)	(0.96)
ROA	0.215	0.198	0.129
	(0.86)	(0.43)	(0.26)
$Discount\ Rate$		-0.250***	-0.248***
		(-5.89)	(-5.60)
$Pct\ Retired$		1.772***	1.746***
		(2.91)	(2.82)
$Pct\ Active$		0.057	0.052
		(0.09)	(0.08)
$Premium/Norm\ Cost$		-0.004*	-0.005*
		(-1.72)	(-1.85)
$PctStock$			0.003
			(1.18)
$PctInvGrade$			0.006**
			(2.00)
Constant	-3.525***	-2.902***	-3.053***
	(-15.52)	(-5.27)	(-5.06)
Pseudo R-squared	0.083	0.141	0.149
Observations	8311	4472	4472

t statistics in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

1.4.3 Firm response to pension buyouts

In line with prior studies ([9], [10]), Table 1.1 presents descriptive evidence of the importance of pension obligations in the consolidated capital structure. Comparing Panels 1A and 1B, non-annuity firms have lower pension obligations (13%) and more long-term debt (25%) compared to their buyout peers (21% and 20% respectively). I investigate whether firms that offload pension liabilities are seeking to reduce total leverage or rather change the composition of debt on the consolidated balance sheet. I first seek to answer whether on average, a pension buyout has a material economic impact in regard to total leverage. I document in the subsequent year, firms raise additional funding through long-term debt financing and this is directly related to the size of the pension buyout. Lastly, I explore the cross-sectional implications of financial constraints as well as the impact on capital expenditures and cash outlays.

Table 1.4 reports results from a spline regression of changes in firm debt on year dummies and a series of controls. The sample contains several firms that engage in more than one pension buyout event. For consistency, I determine the event year by the first instance I observe a firm offloading a portion of the pension obligation. I utilize the following specification to assess the changes on debt composition:

$$\Delta Debt_{i,t} = \gamma Buyout_i \times EventYear_t + \lambda \Delta Control_{i,t} + \phi_t + \epsilon_{i,t} \tag{1.3}$$

The dependent variable takes the form of pension debt, long-term financial debt, or total debt, and is scaled by consolidated assets (sum of pension and balance sheet assets). The sign and magnitude of the γ coefficient is of primary interest. I include a series of controls which may simultaneously impact changes in firm leverage and incorporate year fixed effects. The firm fixed effect is removed as the regression specification is performed in first differences. Column (1) reports results using scaled pension obligations as the dependent variable and $Year_0$ is an indicator variable for the year in which the buyout transaction was executed. These transactions are economically meaningful as total pension obligations decrease by 3.3% in the event year. While I observe no effect in the event year for changes in long-term debt, firms significantly increase (2.2%) balance sheet leverage in the year immediately following the pension buyout. The coefficient estimates on $Year_0$ and $Year_{t+1}$ in column (3) suggest only a minor net effect on consolidated leverage. Results in Table 1.4 are most consistent with firms seeking to change the composition of their capital structure as opposed to reduce overall leverage.

The results shed further light on the degree to which firms sponsoring a DB plan substitute traditional forms of debt with pension liabilities. Relative to the sample averages, the regression results show firms decrease pension liabilities by approximately 16% and subsequently increase financial debt by 11%. This equates to a substitution rate of nearly 70% - more than double the reported estimates previously documented ([9], [10]).

The impact of changes in the pension deficit and the cash flow volatility measure appear as expected in column (1). An increase in each of these variables is consistent with an increase in total pension obligations. However, in column (2), each of these variables are significant and negatively related to long-term debt. The results in column (2) potentially highlight the importance of financial constraints in adjusting capital structure composition. I explore this question in Table 1.5 with additional results reported in the Appendix. Lastly, I control for any firm-year in which a lumpsum transaction is undertaken to ensure these events do not impact the result. As previously noted, lumpsum transactions are an alternative form of pension risk transfer which relieve the plan sponsor of obligations associated with participants accepting the offer. Given the anomalous transaction in 2012 initiated by General Motors, I remove GM from the sample in a robustness test included in the Appendix. There are essentially no changes to the main results.

The decision to purchase a group annuity contract is entirely within management control. This gives rise to endogeneity concerns, which in the current setting, are difficult to fully address. It is possible the relationship I find between pension obligations and

Table 1.4: **Risk Transfer Debt Effects**

Table 1.4 presents results from a regression of changes in several measures of firm leverage on event-year indicators and changes in a series of financial control variables. All dependent variables are scaled by consolidated assets. The dependent variable in column (1), ΔPen Debt, is the change in pension obligations. ΔLT Debt, column (2) is the change in long-term financial debt. The dependent variable in column (3), Δ Tot Debt, represents changes in the sum of pension obligations, long-term, and short-term debt. $Pen\ Deficit$ represents the underfunded status of the pension plan (liabilities less assets). $CFP\ Vol\ Ratio$ is the cash flow volatility measure described in equation (1). MTB is the log of market value of equity, less book value of equity, plus balance sheet assets divided by balance sheet assets. $Total\ Assets$ is the log of balance sheet assets. ROA is defined as net income divided by balance sheet assets. $Collateral$ is the ratio of net property plant and equipment to balance sheet assets. $LumpsumYear$ is a indicator variable equal to one for any firm-year where a sponsor offered a lumpsum buyout. Year fixed-effects are included in each specification. Standard errors are clustered at the firm-level.

	(1) ΔPen Debt / Cons Asset	(2) ΔLT Debt / Cons Asset	(3) Δ Tot Debt / Cons Asset
$Year_{t-3+}$	0.001	0.000	0.001
	(1.06)	(0.00)	(0.52)
$Year_{t-2}$	-0.003	0.005	-0.003
	(-1.35)	(0.77)	(-0.53)
$Year_0$	-0.033***	0.004	-0.024***
	(-7.10)	(0.66)	(-3.99)
$Year_{t+1}$	-0.005*	0.022***	0.017**
	(-1.92)	(2.92)	(2.24)
$Year_{t+2}$	-0.003	-0.017	-0.003
	(-0.87)	(-0.99)	(-0.49)
$Year_{t+3+}$	-0.003	0.004	-0.009
	(-1.19)	(0.73)	(-0.75)
$\Delta Pen\ Deficit$	1.180***	-0.186**	1.047***
	(13.13)	(-2.02)	(8.59)
$\Delta CFP\ Vol\ Ratio$	0.002**	-0.015***	-0.014***
	(2.56)	(-3.30)	(-3.39)
ΔMTB	0.009***	-0.028***	-0.021**
	(4.73)	(-3.31)	(-2.10)
$\Delta BS\ Assets$	-0.032***	0.045**	0.025
	(-7.47)	(2.29)	(1.35)
ΔROA	-0.006	-0.145***	-0.190***
	(-1.26)	(-6.20)	(-4.80)
$\Delta Collateral$	0.041***	0.045	0.113
	(4.43)	(0.59)	(1.44)
$LumpsumYear$	-0.013***	0.008	-0.006
	(-5.91)	(1.18)	(-0.85)
Year FE	Yes	Yes	Yes
R-squared	0.612	0.059	0.156
Observations	7352	7352	7352

t statistics in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 1.5: **Cross-Section of Financial Constraints**

Table 1.5 presents results from a regression of changes in several measures of firm leverage on event-year indicators and changes in a series of financial control variables. Columns (1)-(3) are consist of financially unconstrained firms while columns (4)-(6) consist of financially constrained firms based on the median of the Whited Wu index. All dependent variables are scaled by consolidated assets. The dependent variables ΔPen Debt, ΔLT Debt, ΔTot Debt are the changes in pension obligations, long-term financial debt, and total debt (sum of pension obligations, long-term, and short-term debt) respectively. $Pen\ Deficit$ represents the underfunded status of the pension plan (liabilities less assets). MTB is the log of market value of equity, less book value of equity, plus balance sheet assets divided by balance sheet assets. $Total\ Assets$ is the log of balance sheet assets. ROA is defined as net income divided by balance sheet assets. $Collateral$ is the ratio of net property plant and equipment to balance sheet assets. $LumpsumYear$ is a indicator variable equal to one for any firm-year where a sponsor offered a lumpsum buyout. Year fixed-effects are included in each specification. Standard errors are clustered at the firm-level.

	(1) ΔPen Debt/Cons At	(2) ΔLT Debt/Cons At	(3) Δ Tot Debt /Cons At	(4) ΔPen Debt/Cons At	(5) ΔLT Debt/Cons At	(6) Δ Tot Debt/Cons At
$Year_{t-3+}$	0.001	-0.000	0.002	0.002	-0.002	-0.002
	(0.91)	(-0.00)	(0.63)	(0.88)	(-0.45)	(-0.34)
$Year_{t-2}$	-0.001	0.004	-0.001	-0.006	0.006	-0.008
	(-0.55)	(0.52)	(-0.09)	(-1.58)	(0.56)	(-0.77)
$Year_0$	-0.028***	0.009	-0.013**	-0.045***	-0.012	-0.053***
	(-5.98)	(1.30)	(-2.04)	(-4.27)	(-1.26)	(-3.98)
$Year_{t+1}$	-0.007**	0.027***	0.021**	-0.000	0.014	0.012
	(-2.45)	(2.98)	(2.15)	(-0.01)	(1.05)	(1.06)
$Year_{t+2}$	-0.007**	-0.015	-0.001	0.014	-0.011	-0.001
	(-2.23)	(-0.75)	(-0.08)	(1.45)	(-0.81)	(-0.05)
$Year_{t+3+}$	-0.004	0.004	0.001	-0.002	0.014*	-0.026
	(-1.45)	(0.62)	(0.23)	(-0.32)	(1.73)	(-0.62)
$\Delta Pen\ Deficit$	1.085***	-0.093	0.846***	1.219***	-0.203	1.147***
	(20.09)	(-0.94)	(8.85)	(10.38)	(-1.52)	(7.73)
ΔMTB	0.013***	-0.012	0.001	0.006***	-0.033***	-0.030**
	(4.69)	(-0.96)	(0.12)	(2.79)	(-3.55)	(-2.40)
$\Delta BS\ Assets$	-0.029***	0.044***	0.022*	-0.036***	0.067**	0.042*
	(-5.32)	(3.28)	(1.66)	(-5.56)	(2.54)	(1.66)
ΔROA	0.001	-0.150***	-0.255***	-0.008	-0.151***	-0.179***
	(0.15)	(-3.10)	(-5.45)	(-1.48)	(-5.80)	(-3.85)
$\Delta Collateral$	0.045***	0.145**	0.216***	0.040***	-0.005	0.056
	(2.81)	(2.07)	(2.96)	(3.39)	(-0.05)	(0.49)
$LumpsumYear$	-0.007***	0.008	0.000	-0.025***	0.012	-0.015*
	(-4.21)	(0.89)	(0.03)	(-4.66)	(1.47)	(-1.70)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.552	0.066	0.166	0.652	0.070	0.166
Observations	3817	3817	3817	3537	3537	3537

t statistics in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

long-term debt is driven by an omitted variable, which leads to the subsequent increase in leverage. I attempt to partially address some concern in Table 1.6. Specifically, I interact the $Year_0$ and $Year_{t+1}$ indicators with the size of the pension buyout transaction (Settled). In column (2) I observe an increase in long-term debt that is proportional to the size of the pension buyout. The coefficient on interaction of $Year_{t+1} \times Settled$ suggests firms that pursue a larger buyout offer proceed to raise a greater amount of external debt financing. If an omitted variable is responsible for the increase in long-term debt in the following year it must also be commensurate with the timing and decrease in pension obligations resulting from the pension buyout.

As discussed previously, the decision to offload the pension liability could be motivated by either the desire to change the composition of debt or reduce total leverage. The former would be consistent with a reduction in the volatility of funding rather than level while the latter suggests a need to preserve liquidity. [8] demonstrate financially constrained firms have a higher sensitivity to cash flows and preserve cash anticipating the future constraints. Unconstrained firms have no need to hold cash given unrestricted access to external financing. Additionally, [27] show pension deficits are driven by financial constraints and lead to higher costs of bank financing.

I explore these two channels in Table 1.5. I split the sample based on the median of the [28] financial constraints index (WW index) and repeat the specification in Table 1.4. In robustness tests, I confirm these results in the Appendix using the z-score and credit ratings as alternative proxies for financial constraints. Columns (1)-(3) comprise the sample of less financially constrained firms, while columns (4)-(6) include firms facing greater constraints. Comparing columns (2) and (4), I find debt substitution is entirely concentrated in the less constrained firms. These firms have a lesser need to safeguard against future cash shortfalls, while the constrained firms seek to reduce volatile pension liabilities. Furthermore, columns (3) and (6) substantiate the finding in total firm leverage appears to increase in $Year_{t+1}$ for those least likely to experience constraints. The continued reduction in pen-

Table 1.6: **Risk Transfer Debt Effects - Total Obligation Settled**

Table 1.6 presents results from a regression of changes in several measures of firm leverage on event-year indicators and changes in a series of financial control variables. All dependent variables are scaled by consolidated assets. The dependent variable in column (1), ΔPen Debt, is the change in pension obligations. ΔLT Debt, column (2) is the change in long-term financial debt. The dependent variable in column (3), Δ Tot Debt, represents changes in the sum of pension obligations, long-term, and short-term debt. $Settled$ is the size of pension obligations settled through the buyout scaled by consolidated assets. $Pen\ Deficit$ represents the underfunded status of the pension plan (liabilities less assets). $CFP\ Vol\ Ratio$ is the cash flow volatility measure described in equation (1). MTB is the log of market value of equity, less book value of equity, plus balance sheet assets divided by balance sheet assets. $Total\ Assets$ is the log of balance sheet assets. ROA is defined as net income divided by balance sheet assets. $Collateral$ is the ratio of net property plant and equipment to balance sheet assets. $LumpsumYear$ is a indicator variable equal to one for any firm-year where a sponsor offered a lumpsum buyout. Year fixed-effects are included in each specification. Standard errors are clustered at the firm-level.

	(1) ΔPen Debt / Tot Asset	(2) ΔLT Debt / Tot Asset	(3) Δ Tot Debt / Tot Asset
$Year_0$	-0.018***	0.001	-0.013**
	(-3.66)	(0.20)	(-2.06)
$Year_0 \times Settled$	-0.422***	0.068	-0.291**
	(-5.58)	(0.63)	(-2.32)
$Year_{t+1}$	-0.005*	0.014*	0.013*
	(-1.71)	(1.85)	(1.69)
$Year_{t+1} \times Settled$	-0.001	0.243**	0.126
	(-0.02)	(2.40)	(1.02)
$Settled$	0.008	-0.003	0.004
	(0.58)	(-0.13)	(0.13)
$\Delta Pen\ Deficit$	1.180***	-0.188**	1.047***
	(13.13)	(-2.04)	(8.58)
$\Delta CFP\ Vol\ Ratio$	0.002**	-0.015***	-0.015***
	(2.20)	(-3.34)	(-3.45)
ΔMTB	0.008***	-0.028***	-0.021**
	(4.62)	(-3.30)	(-2.13)
$\Delta BS\ Assets$	-0.032***	0.046**	0.025
	(-7.49)	(2.30)	(1.35)
ΔROA	-0.006	-0.145***	-0.190***
	(-1.29)	(-6.21)	(-4.81)
$\Delta Collateral$	0.040***	0.044	0.113
	(4.37)	(0.59)	(1.43)
$LumpsumYear$	-0.011***	0.008	-0.005
	(-5.55)	(1.22)	(-0.72)
Year FE	Yes	Yes	Yes
R-squared	0.619	0.059	0.156
Observations	7352	7352	7352

t statistics in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

sion liabilities in years subsequent to the first event year (column (1), is consistent with either these firms engaging in additional risk transfer events or potentially accruing liabilities at a slower rate after the initial transaction. Table 1.5 demonstrates both the need to reduce volatile liabilities as well as total leverage are considerations for pension buyout transactions.

It is well understood financially constrained firms may withhold investment due to costly external finance. Namely, a potential indicator of constraint, higher cash flow volatility, is associated with higher costs of external capital [14]. Less predictable cash flows increase the likelihood a firm will face a cash shortfall during times of positive investment opportunities. The results in Table 1.5 provide consistent evidence in that these firms are less prone to increase long-term debt after offloading DB obligations.

A reduction in cash flow volatility around pension buyouts would then be expected to provide managers with a greater degree of certainty around their investment decisions. In Table 1.7, I investigate cash outlays amid pension buyout transactions. First, I test whether additional cash contribution are needed to fully fund these transactions. If on average, only sufficiently overfunded DB sponsors (pension assets greater than liabilities) engage in risk transfer transactions, then no additional contributions would be necessary. The results in column (1) suggest this is not the case. Firms materially increase cash contributions to the pension in the event year and proceed to decrease contributions in the year immediately following as total obligations are lower. In columns (2) and (3), I test the response of capital expenditures for the entire sample as well as those firms falling above the median of the WW index, respectively. Investment significantly increases in the year of the pension buyout and the effect is most pronounced for financially constrained firms ($Year_0$ and $Year_{t+2}$). Importantly, I control for annual changes in cash flows (excluding pension contributions) to ensure the increases to pension contributions and investment are not driven by an anomalous high cash flow year for the firm. In untabulated results, I find no effect on capital expenditures for financially unconstrained firms. I further explore research and

Table 1.7: **Investment Changes**

Table 1.7 presents results from a regression of changes in several forms of discretionary cash outlays. All dependent variables are scaled by balance sheet assets. The dependent variable in column (1) is the change in pension contributions. In columns (2) and (3) the change in capital expenditures scaled by lagged balance sheet assets serves as the dependent variable. Column (3) is limited to only financially constrained firms according to the WW index. Columns (4) and (5) represent changes research and development costs and dividends. $Pen\ Deficit$ represents the underfunded status of the pension plan (liabilities less assets). MTB is the log of market value of equity, less book value of equity, plus balance sheet assets divided by balance sheet assets. $Total\ Assets$ is the log of balance sheet assets. ROA is defined as net income divided by balance sheet assets. $Cashflow$ is the ratio of cash flow to balance sheet assets. $LumpsumYear$ is a indicator variable equal to one for any firm-year where a sponsor offered a lumpsum buyout. Year fixed-effects are included in each specification. Standard errors are clustered at the firm-level.

	(1) ΔContributions/Assets	(2) ΔCapEx/Assets	(3) ΔCapEx/Assets	(4) ΔR&D/Assets	(5) ΔDiv/Assets
$Year_{t-3+}$	-0.000	0.000	0.001	-0.000	0.000
	(-0.75)	(0.09)	(0.28)	(-0.65)	(0.01)
$Year_{t-2}$	-0.001	0.001	-0.003	0.001	0.001
	(-0.38)	(0.40)	(-1.09)	(1.27)	(1.26)
$Year_0$	0.007***	0.003**	0.007**	0.001	0.001
	(2.95)	(2.00)	(2.39)	(0.98)	(0.64)
$Year_{t+1}$	-0.009***	0.002	0.000	0.001	-0.000
	(-3.13)	(1.31)	(0.10)	(1.02)	(-0.58)
$Year_{t+2}$	-0.003	0.002	0.008**	-0.000	0.003
	(-1.30)	(1.41)	(2.26)	(-0.07)	(1.34)
$Year_{t+3+}$	-0.000	0.001	0.003	-0.001	-0.002
	(-0.04)	(0.36)	(1.44)	(-1.03)	(-1.60)
$\Delta Pen\ Deficit$	-0.040	-0.021	-0.026	0.095	-0.010
	(-1.61)	(-1.03)	(-0.98)	(1.37)	(-1.13)
ΔMTB	0.001	0.003	0.006	0.005*	0.004***
	(1.11)	(1.18)	(1.57)	(1.65)	(3.97)
$\Delta BS\ Assets$	-0.004***	0.024***	0.027***	-0.012***	-0.011***
	(-5.37)	(10.93)	(8.56)	(-5.39)	(-8.83)
ΔROA	-0.002	0.023***	0.022***	-0.017*	-0.001
	(-0.88)	(4.66)	(3.69)	(-1.87)	(-0.36)
$\Delta CashFlow$	0.001	-0.001	0.001	-0.016	0.003
	(0.78)	(-0.12)	(0.10)	(-1.15)	(0.80)
$LumpsumYear$	-0.001	-0.001	-0.002	-0.001	0.002**
	(-0.94)	(-0.48)	(-0.60)	(-1.08)	(2.32)
Year FE	Yes	Yes	Yes	Yes	Yes
R-squared	0.038	0.052	0.058	0.077	0.049
Observations	6753	7290	3517	7290	7237

t statistics in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

development costs (column (4)) and dividends (column (5)) and find no material effects on average or in either subsample.

1.5 Shareholder returns and pension buyouts

Pension buyouts have competing implications with respect to firm value. All else equal, lower systematic risk through a reduction in volatile pension obligations should increase firm equity value. However, the premium associated with the group annuity along with a significant increase in pension contributions documented in Table 1.7 suggest a negative cash flow effect. [15] conclude the market does not anticipate future cash demands of the pension obligation until they are realized. Even under the pretense that market participants do anticipate future pension contributions, in the context of a pension buyout, these cash flows are unexpectedly accelerated. The literature has been divided on the issue of market efficiency and corporate pension obligations. While some researchers have found consistency with efficient markets,[11] others cite the opacity of pension accounting as reason for the market falling short in anticipating pension implications.[12] It is then an empirical question as to whether the shareholder response to a buyout transaction has an impact on stock returns. In the case that the market does react, is the response driven by the positive news of lower future volatility or negative cash flow news to fund the buyout? In this section, I perform short and long horizon event studies which demonstrate a significant negative response to pension buyout transactions. I then decompose individual stock returns following [16] in efforts to determine the dominant news component driving abnormal returns.

For the short horizon analysis, I estimate cumulative abnormal returns (CAR) using the [35] three-factor model where:

$$R_{i,t} - r_{f,t} = \alpha_i + \beta_{i1}(R_{m,t} - r_{f,t}) + \beta_{i2}HML_t + \beta_{i3}SMB_t + \epsilon_{i,t} \tag{1.4}$$

[11] [11]; [29]; [30];[31]

[12] [32]; [33];[34]

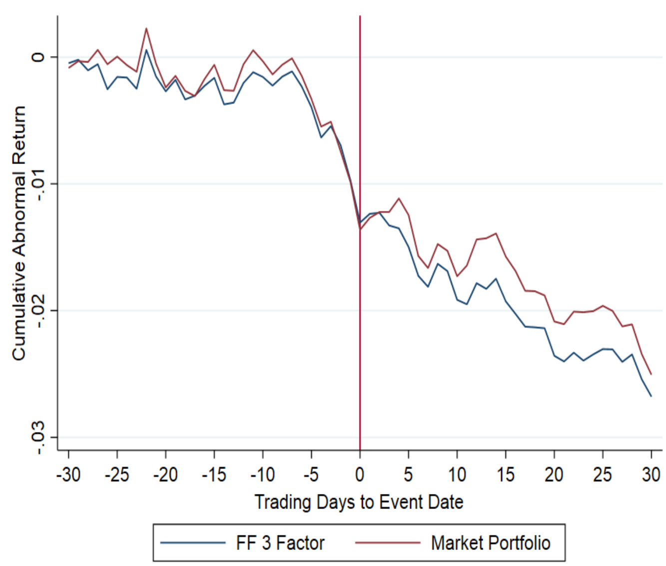
$$AR_{i,t} = r_{i,t} - \hat{r}_{i,t} \tag{1.5}$$

$$CAR_{i,\tau} = \sum_{t=\tau}^{\tau} AR_{i,t} \tag{1.6}$$

I also compare results to an estimation using a market model in Figure 1.3, and display the results of the raw cumulative returns against cumulative market returns in Figure 1.4. An estimation window of [-30,-210] days prior to the event date is used for purposes of calculating predicted returns. Table 1.8 shows the statistical results from the three-factor event study. Panel A and Panel B report cumulative abnormal returns for several short horizon windows while Panel C includes results from long horizon tests. There are 132 (110) pension buyout transactions that I could reliably match to return data for the short (long) horizon.

Figure 1.3: Short Horizon: Cumulative Abnormal Returns

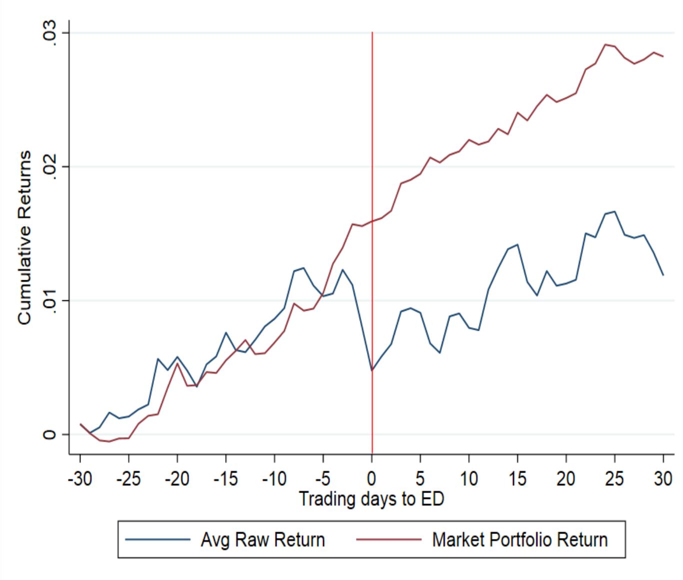
Figure 1.3 shows the cumulative cumulative abnormal returns using both a three-factor model as well as market model in the 30 day window preceding and following the date of a pension buyout transaction



For the full sample, including the day prior and five-day period immediately follow-

Figure 1.4: Short Horizon: Raw Return vs. Market Return

Figure 1.4 shows the cumulative equal-weighted raw returns as well as cumulative returns of the market portfolio in the 30 day window preceding and following the date of a pension buyout transaction



ing the announcement, firms experience a negative cumulative abnormal return of 0.7%. This magnifies to -1.8% in the 30-day window post transaction. In each panel, I further split the sample by the median of the WW index. The firms exhibiting a *lower* degree of financial constraint account for the majority of negative CARs reaching -2.9% in the negative one to positive thirty day window. [36] similarly find negative returns using the market model and smaller sample. Investors may perceive the use of cash to fund pension buyouts as suboptimal for these firms if they could rather borrow from capital markets to fund future pension shortfalls. Alternatively, it may peak concern to shareholders who previously placed minimal emphasis on the pension obligations of these firms. Returns for the financially constrained sample are negative, yet statistically insignificant. The negative and significant cumulative abnormal returns suggest negative cash flow news from either higher than expected contributions or accelerated contributions. Ex ante, value maximizing managers would be perceived to prioritize a reduction in volatility, while investors place greater weight on the near term cash implications.

Table 1.8: **Abnormal Returns - Shareholder Reaction to Buyout Events**

Table 1.8 shows short horizon cumumlative abnormal returns around the event window of pension buyout transactions. Panel A includes CAR windows beginning the day prior to the recorded event, [-1,X]. Panel B shows event windows beginning five days prior the the event, [-5,X]. I use the Fama French 3-factor model to estimate returns over the [-210,-30] day period for short-horizon event windows. Panel C displays the results from long-horizon buy-and-hold cumulative abnormal returns relative to size and book-to-market matched portfolios from [0,X] month horizons. The first row in each panel consists of the full sample of 133 events. The second two rows are divided by into financially unconstrained firms (Fin Uncon) and financially constrained (Fin Con) according to the median of the [28] contraints index.

Panel A - Short Horizon	(1)	(2)	(3)	(4)
	[-1,5]	[-1,10]	[-1,20]	[-1,30]
CAR (All)	-0.007*	-0.012**	-0.016**	-0.018**
	(-1.69)	(-2.04)	(-2.29)	(-2.18)
CAR (Fin Uncon)	-0.010*	-0.014**	-0.023**	-0.029***
	(-1.77)	(-2.12)	(-2.60)	(-2.88)
CAR (Fin Con)	-0.006	-0.010	-0.009	-0.007
	(-0.80)	(-0.99)	(-0.82)	(-0.58)
Panel B - Short Horizon	(1)	(2)	(3)	(4)
	[-5,5]	[-5,10]	[-5,20]	[-5,30]
CAR (All)	-0.014**	-0.018**	-0.022***	-0.024***
	(-2.36)	(-2.58)	(-2.79)	(-2.69)
CAR (Fin Uncon)	-0.017**	-0.021**	-0.030***	-0.036***
	(-2.15)	(-2.41)	(-2.86)	(-3.22)
CAR (Fin Con)	-0.011	-0.014	-0.013	-0.012
	(-1.24)	(-1.34)	(-1.18)	(-0.89)
Panel C - Long Horizon	(1)	(2)	(3)	(4)
	[0,3]	[0,6]	[0,9]	[0,12]
CAR (All)	-0.040***	-0.038**	-0.060***	-0.055**
	(-3.20)	(-2.29)	(-2.86)	(-2.31)
CAR (Fin Uncon)	-0.045***	-0.049*	-0.070**	-0.058
	(-3.18)	(-1.88)	(-2.11)	(-1.59)
CAR (Fin Con)	-0.033	-0.026	-0.051*	-0.050*
	(-1.59)	(-1.29)	(-1.94)	(-1.73)

t statistics in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Motivated by the evidence in Figure 1.3, in Panel B, I extend the pre-event window to 5 days prior to the event. The figure clearly shows abnormal returns fluctuate around zero until approximately five days prior to the event date when they begin to trend downward. Comparing the results in Panels A and B, abnormal returns fall an additional 0.7% immediately prior to the transaction announcement. Through carefully parsing SEC filings, news articles, and Form 5500 data, I record the first instance where a firm has either explicitly reported that it has purchased a group annuity or mentioned that it will in the future. In many cases, the first time a buyout is reported is in an annual 10-K or a quarterly 10-Q filing. Depending on size, firms have up until 90 days to file regulatory forms after fiscal year end. Generally, the filing is posted sooner, yet it is virtually always in concert with, or a few days after the form 8-K filing announcing their quarterly or full year earnings. Pension buyouts often trigger accounting settlement charges resulting from accelerated unamortized losses, which may appear in earnings and prior to the release of the 10-K/Q. These settlement charges can be considerable in some instances. In the second quarter of 2015, Kimberly-Clark Corporation reported a pre-tax pension settlement charge of $1.3 billion tied to a $2.5 billion buyout transaction. The charge was equivalent to the entire decline in operating income relative to the prior year.

In Panel C, I investigate the results from a long horizon event study to determine if returns revert over time. The accounting, cash flow, and volatility implications of a buyout transaction are complex potentially leading to lag for information to be fully reflected in prices. However, I do not observe signs of a reversal. Returns for annuity buyout firms continue to underperform the market and matched-portfolio peers. In the three months after the event date, buyout firms experience a -4.0% abnormal return, extending to -5.5% over the following year. In line with the short horizon results, the least financially constrained firms exhibit the greatest degree of negative relative returns. Figure 1.5 and Figure 1.6 display the cumulative abnormal return series and raw return series, respectively. Prior to the announcement, cumulative abnormal returns appear moderately positive before declining dramatically in the following three months. Similarly, in the six months prior to the event, raw returns track the market rather closely and diverge thereafter.

Figure 1.5: Long Horizon: Cumulative Abnormal Returns

Figure 1.5 shows cumulative abnormal returns using portfolios of size and book-to-market matched portfolios as well as the market model in the six month window preceding the transaction to the twelve month window following.

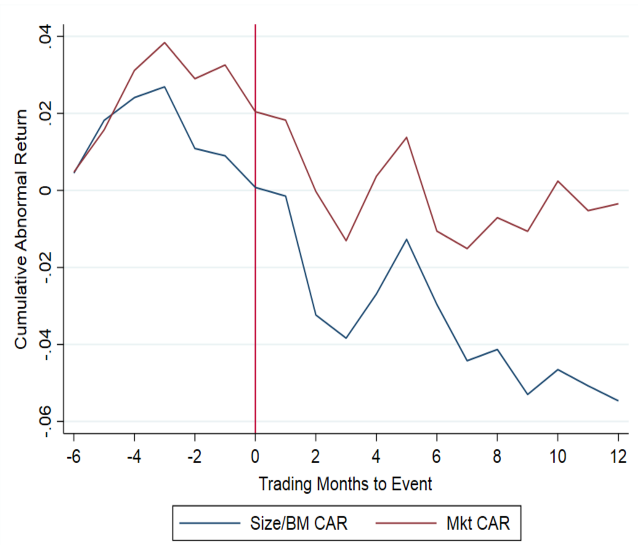
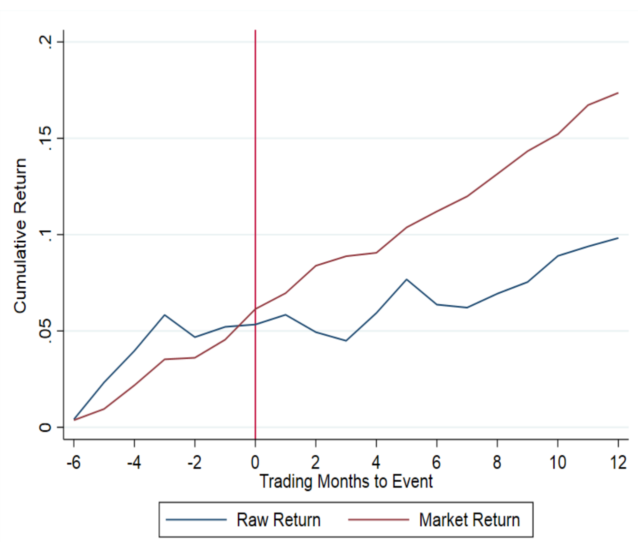


Figure 1.6: Long Horizon: Raw Return vs. Market Return

Figure 1.6 shows cumulative equal-weighted raw returns for the portfolio of annuity buyout firms as well as the market in the six month window preceding the transaction to the twelve month window following.



The decision to pursue a buyout transaction is endogenous giving rise to reverse causality concerns. One potential explanation for the long horizon underperformance is that these firms continue to divert cash flow to aggressively fund the pension as part of a long-term strategy to de-risk the plan and reduce PBGC variable rate premiums. Numerous institutional surveys from reputable consultants and asset managers confirm this recent trend among sponsors.[13] Alternatively, firms may anticipate future volatility (from operations or the pension liability) continuing to rise and seek to partially offset the risk by reducing pension obligations.

1.5.1 Return decomposition

As described previously, the impacts of the pension obligation on firm value are multifaceted. To further explore the source of negative abnormal returns in Table 1.8, I leverage the construct of [16] to decompose returns into the effects from changes in cash flow expectations and changes in discount rates. The VAR model proposed by the author incorporates the cross-sectional predictability of stock returns, namely size, book-to-market, and prior returns. The need for accounting variables then restricts the model to a quarterly frequency at a minimum. Aside from substituting quarterly returns for annual returns, I follow the author's design of returns in a vector autoregressive model:

$$z_{i,t} = \Gamma z_{i,t-1} + u_{i,t} \tag{1.7}$$

where the first element of the vector of state variables, $z_{i,t}$, is the market-adjusted stock return and remaining elements include market-adjusted figures for log profitability and log book-to-market ratio. Γ is constant across both firms and time. The time variation is introduced through the innovations in the error term which is not necessarily correlated across firms. The return decomposition is then defined by the following equation introduced by

[13] Vanguard 2019 Survey of Pension Sponsors; MetLife 2019 Pension Risk Transfer Poll; Mercer Pension Risk Transfer Asset-in-Kind Considerations

[37]:

$$e1' \equiv [1\ 0\ ...\ 1] \tag{1.8}$$

$$\lambda' \equiv e1'\rho\Gamma(I-\rho\Gamma)^{-1} \tag{1.9}$$

The decomposition shows discount rate and cash flow news are then expressed as:

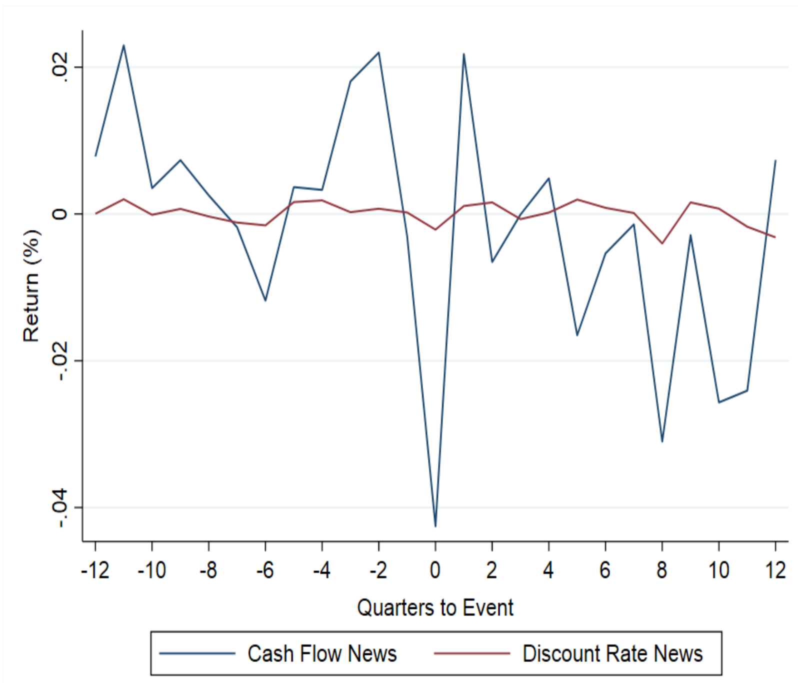
$$DR\ News = \lambda' u_{i,t} \tag{1.10}$$

$$CF\ News = (e1' + \lambda')u_{i,t}. \tag{1.11}$$

For each quarter, I derive the individual components and plot them in Figure 1.7. I witness a statistically significant negative impact from cash flow news in the event quarter. Comparing the results to the long horizon event study estimates confirms the majority of negative abnormal returns are experienced in the months surrounding the pension risk transfer event. Regression results are included in the Appendix. Cash flows are not explicitly included in the model, rather the related news component is a residual after calculating expected return news. Furthermore, pension contributions are not recorded as an expense in the accounting sense. As mentioned in the previous section though, they usually result in substantial settlement charges which would directly impact earnings in the quarter the pension buyout transaction was executed.

Figure 1.7: Cash Flow News v. Discount Rate News

Following [16], I decompose firm-level quarterly returns of pension buyout firms into their cash flow and discount rate news components. The graph shows a 3-year period prior to and after the recorded transaction.



1.6 Conclusion

In this paper, I leverage pension risk transfer events to provide new evidence of the impact of pension obligations on capital structure, investment policy, and shareholder returns. Due to lack of existing data sources, I manually construct a database of pension buyout and lumpsum events. The regulatory and market environment affecting pension liabilities levels has changed dramatically over the past decade leading to increased funding volatility. The DB obligation is shown to be a significant contributor to rising cash flow volatility to external stakeholders, while such volatility is a driving factor in the decision to engage in a group annuity purchase. Pension buyout events are economically material events equating to over 3% of consolidate firm assets on average.

The degree of financial constraints a firm faces plays a pivotal role in corporate policy decisions surrounding these transactions. While unconstrained firms, with access to external capital, substitute pension debt for financial at a one-to-one ratio, financially constrained firms prioritize cash preservation through a reduction in total leverage. Furthermore, I document the latter subset of firms significantly increase capital expenditures consistent with a reduction in future uncertainty of cash shortfalls.

The pension risk transfer market is still in its nascenct stages. Total U.S. defined benefit pension assets were over $2.5 trillion at the end of the sample period. The size and volume of buyout transactions is expected to escalate over the coming years making the findings of this study and additional research on the pension risk transfer market increasingly relevant going forward.

CHAPTER 2

PENSION OVERHANG AND CORPORATE INVESTMENT

2.1 Introduction

"Pension liabilities are debt." [38]

Defined benefit (DB) pension plans sponsored by U.S. corporations have approximately $3.21 trillion in assets in 2017 with the present value of pension liabilities representing over 16% of total firm assets. But, assets designated to pay future benefits amount to only approximately 85% of the pension liability[1], suggesting pension beneficiaries are material creditors to the firm. While the underinvestment problem caused by debt overhang ([39]) is well understood ([40], [41]), the role of pension obligations on firm investment policy is less clear ([12], [13]). In this paper, we exploit an exogenous, universal increase in pension discount rates mandated by MAP-21 (significantly decreased pension liabilities), to investigate whether firm investment is affected by its unfunded pension liabilities.

Debt overhang reflects a wedge between the value of investment to the firm and the value to shareholders ([40]). Unlike ordinary debt obligations, the pension liability and annual payments to fund associated benefits are dependent on numerous market, regulatory, and actuarial inputs, which are subject to frequent updating. In the context of [39], the option value of future investment to shareholders is dependent on the cost of investment and the required payments to creditors. For a firm sponsoring a defined benefit pension plan with variable future payments to fund the long-term liability, the option value is considerably less certain. Unfunded pension obligations may therefore have significant incremental effects on the underinvestment problem resulting from "risky debt."

[1]Figures from U.S. Department of Labor Private Pension Plan Bulletin Historical Tables and Graphs 1975-2017 and our sample data from IRS Form 5500 filings and Compustat prior to the adoption of MAP-21

Pension obligations are unique in terms of both the variable size of the liability as well as collateral (invested pension assets). Pension beneficiaries are creditors to the firm to the extent a DB pension plan is underfunded or may become underfunded in the future ([1]; [17]). The unfunded pension liability is exacerbated during periods of economic stress as discount rates and asset prices fall. In a default scenario, pensioners assume a relatively senior status that is generally at least *pari passu* to unsecured creditors and in some cases all, or a portion of the pension obligation may claim a senior status. The highly regulated nature of pensions along with the numerous stakeholders makes it difficult to restructure pension liabilities. As a result, the value of investment to a firm sponsoring a DB pension plan is less certain, thus exacerbating underinvestment due to debt overhang. The pension is generally the largest non-traditional obligation of our sample firms while recent literature ([42] has highlighted the role of overhang in extending beyond traditional debt financing.

We examine investment policy resulting from a shock to firm pension liabilities due to MAP-21 in a difference-in-differences framework. MAP-21 was a transportation funding bill passed in 2012. The legislation initiated a higher interest rate methodology at which future pension disbursements are to be discounted, effectively lowering the present value of liabilities. The newly instituted discount rates were on average 200 basis points higher than the existing rates. The change to discount rates was part of an offsetting revenue component of the law as lower, tax-deductible pension contributions were expected to increase corporate tax bills. The shock is plausibly exogenous to the firm's investment opportunity set as the discount rates are constant across firms and MAP-21 affected nearly all private plans covered under The Employee Retirement Income Security Act of 1974 (ERISA).

To test the effects of pension debt overhang, we augment the overhang measure from [40] and [43] (HLW) and construct an overhang measure incorporating pension obligations. Controlling for Tobin's Q, cash flow, and established measures of (financial) debt overhang, we find an incremental impact attributable to overhang from unfunded pension obligations. A one standard deviation change in our *pension* overhang variable is associated with an approximate 5.5% change in investment. Comparatively, a one standard deviation change in the debt overhang measure is associated with an approximate 6.6% change in investment.

We observe no significant changes to investment for all firms with underfunded pension plans prior to the law change. But, firms that have a higher pension overhang (above median) prior to MAP-21, ultimately increase investment by 13% as a consequence to the reduction in their pension liability. These effects are strongest for entities that are most likely to face external financing constraints as proxied by the Size-Age index of [44], the textual analysis index of [45], cash holdings, and firm size. Additionally, we find evidence that firms encumbered by higher pension obligations have lower credit ratings on average. However post MAP-21, those firms with ex ante high pension overhang are more likely to experience a credit rating upgrade, consistent with an alleviation of their pension liability.

We continue in examining the cross-section of CEO compensation as pay-for-performance sensitivity has been shown to impact investment policy ([46]). Chief executive officers (CEOs) with more pay-for-performance sensitivity (as measured by higher delta and vega of their stock and option compensation) increased their investment rate to a greater extent after passage of the law.[2] Further, we find that CEOs with a longer horizon (those with compensation with a longer vesting schedule) invest considerably more after the passage of the law.

The future employee benefits associated with corporate defined benefit pension plans generate a long-term liability for the firm. If the firm has not accumulated sufficient assets dedicated to funding promised benefits, mandatory annual contributions are required to make up for the shortfall. Corporate investment policy for a financially constrained firm can therefore be affected through two separate channels: (1) the cash flow effects resulting from annual contributions and (2) the debt overhang effect associated with long-term unfunded pension obligations.

[2] Delta, computed as the sensitivity of the manager's wealth to the firm's stock price, measures the dollar gain or loss in the manager's wealth as the firm's stock price changes by a certain amount. Vega, measures the sensitivity of the manager's wealth to the firm's stock return volatility.

Previous work has explored the cash flow channel with mixed results ([12]; [13]; [47]; [48]). One of the reasons that cash flows may not be the primary channel through which pension shortfalls impact investment is that mandatory contributions are economically minor relative to both assets and cash flow (approximately 0.2% of assets for the median firm, 1% of cash flow) for the majority of firms in a given year. Additionally, a firm has optionality in its contributions above mandatory minimums providing plan sponsors the ability to smooth contributions over time. In this paper, we highlight an alternative channel through which the pension funding impacts firm investment policy — the incremental overhang effect from unfunded pension liabilities.

MAP-21 was intended to increase additional revenue to the government by lowering tax-deductible pension contributions. Therefore, we also seek to rule out an alternate hypothesis, that the impact of MAP-21 on investment is through the marginal tax rate channel. Firms with a higher marginal tax rate prior to MAP-21 may have an incentive to increase investment to maximize tax deductions. We do not find evidence the impact of pension overhang on investment that we document is driven by high marginal tax rate firms.

Over the last decade, many firms have frozen their defined benefit plans, where as a result, the plan is closed to new entrants and in some instances current employees are transitioned into a defined contribution plan. We conduct robustness tests to make sure that the differences in duration of plan liabilities between firms with frozen DB plans and those with open DB plans are not driving our results.

The impact of pension liabilities on corporate policies has garnered increasing attention over recent years, yet remains relatively unexplored compared to traditional measures of firm leverage. This may be due to the off-balance sheet presentation of pension liabilities prior to 2006 and the unique and complex features involved in determining pension liabilities. [49] models the firm's investment decision in the context of underfunded pension liabilities and argues the pension liability may affect both the level and riskiness of future investment. [50] find that for Compustat firms with a DB plan, accounting for the underfunded portion of pension plans increases their leverage ratio by about a third. [51] find that increases in mandatory pension contributions increase the overall cost of capital to firms that are already financially constrained. In addition, [11] show the equity cost of capital for firms with DB plans reflects the risk of their pension plan, thus impacting the net present value of their investment opportunities. Our paper is related to [48], who also makes uses of MAP-21 to investigate the cash flow effects of pension policy on corporate payouts and cash holdings, but does not find an effect on firm investment. In contrast, using a measure of pension overhang, we find that after MAP-21, affected firms increased their investment.

We contribute to this literature by demonstrating that underfunded pension plans can inhibit investment through an overhang channel above and beyond the potential impact from pension-related cash flows. We emphasize the unique characteristics of pension liabilities which deserve consideration in the context of debt overhang. In this respect, our paper is similar in spirit to [42] who studies the impact of a liability not considered under traditional financial debt, the mine reclamation liability, on the investment policy of Canadian resource extraction companies.

Empirical analysis of pension liabilities and corporate actions have potential endogeneity concerns given that a firm has varying degrees of flexibility in the choices to offer, freeze, terminate, and fund its pension plan. We take advantage of a universal shock to pension liabilities through MAP-21 to mitigate these concerns.

The rest of the paper is organized as follows. We present the institutional details of defined benefit plans and MAP-21 in brief and discuss the empirical specifications in Section II. Section III describes the data and summary statistics. Our main empirical results are presented in Section IV. Section V presents results from robustness tests and Section VI concludes the paper.

2.2 Defined Benefit Pension Plans

2.2.1 Corporate Pension Schemes

There are two main types of corporate pension plans, defined benefit (DB) and defined contribution (DC). The key differentiating factor is in which party bears the full market and longevity risk associated with funding retirement benefits. For a DB plan, the sponsor (employer) bears this risk, while the individual beneficiary must manage these risks in a DC plan. DB pension plans provide an annuity, financed by the sponsor, to plan participants in retirement. The annuity payments are usually determined by employee tenure, age, salary and potentially various other inputs depending on the plan. Whereas in a DC pension, the plan sponsor is only required to make annual cash contributions to employees' individual accounts based on a pre-specified benefit formula determined at the sponsor's discretion. As part of a DC pension plan, each employee is then responsible for the asset allocation of his or her own retirement account and assumes all associated asset and longevity risk. Importantly, DC plans do not create a long-term liability for the firm. We thus restrict the ensuing analysis and conclusions to firms with at least one DB pension plan.

A DB pension plan is governed under the rules laid out by ERISA. The liability is calculated as the present value of future benefit payments owed to plan participants. The law stipulates strict requirements for actuarial assumptions in determining longevity, how liabilities should be calculated, and for payments toward any unfunded plan liabilities through mandatory cash contributions. We provide additional details on mandatory contributions in Section 2.2. The total assets of a pension plan can be defined as the cumulative sum of all prior firm contributions, plus gains (losses) on invested assets, and less payouts to plan participants. The assets dedicated to the pension plan are held in a separate legal entity and cannot be accessed by the firm for corporate cash needs except for the purpose of paying out benefits and related pension plan expenses. In the case of a plan termination, the firm will garner any residual assets remaining after all benefits have been paid out to plan participants.

The funded status of a DB pension plan is defined as the ratio of dedicated pension assets to the pension liability. In any particular year, a plan may be underfunded (assets less than the liability) or overfunded (assets greater than the liability). The funded status is then subject to volatility from changes in both pension assets and liabilities. The ratio may be impacted by the returns on invested plan assets, employer contributions toward any funding shortfall, and changes to market or actuarial assumptions in calculating the liability. Firms can, and often do, fluctuate between an underfunded and overfunded status through time. In this paper, we focus on the changes MAP-21 imposed on determining the pension liability.

The total pension liability is the present value of all annuity payments owed to each workforce member covered under the pension plan. It is a function of numerous factors and actuarial assumptions including discount rates, longevity expectations, benefit structure as well as the size, age, and tenure of the part of the workforce covered by the plan. The accounting standards for determining DB plan liabilities differ between Securities and Exchange Commission (SEC) filings and IRS Form 5500 filings. The former must conform to Financial Accounting Standards Board (FASB) requirements while the latter must adhere to the stipulations set forth in ERISA. The pension liability, for ERISA purposes, is defined as the accumulated benefit obligation (ABO) - the present value of accrued benefits as described by the Internal Revenue Code (IRC). Unlike the projected benefit obligation (PBO) used in SEC reporting, the ABO does not incorporate future expected changes in compensation levels. In general, FASB offers more discretion in terms of actuarial assumptions. The rules outlined by ERISA are the binding constraint with respect to determining annual mandatory contributions. The effects of MAP-21 only impact IRS filing data and do not change the standards for SEC reporting. We therefore restrict the pension data to the annual Form 5500 filings in our empirical analysis.

2.2.2 MAP-21/Moving Ahead for Progress in the 21st Century Act

MAP-21 was enacted with the primary purpose of reauthorizing government spending on U.S. transportation infrastructure. Signed into law in July 2012, the bill allotted for $105 billion of expenditures on highway, transit, bike, and pedestrian programs.[3] As part of the revenue to offset costs incurred, the bill mandated a change in the discount rates used to calculate single-employer defined benefit pension liabilities. The revenue raising component intended to increase taxable income on corporations by lowering tax-deductible contributions to pension plans.[4]

Corporate pension contributions are tax-deductible up to certain thresholds and are calculated on an individual plan basis. In general, a firm is required to make pension contributions equal to the sum of the normal cost and an installment of any funding deficit based on a seven-year amortization. The normal cost consists of all accrued benefits to participants for a plan-year and any annual expenses planned to be paid from the assets of the plan. The size of required plan contributions is based on the funding target attainment percentage (funded status hereon) as well as the total liability of the pension plan. By raising the effective discount rate, MAP-21 decreases the pension liability by ERISA standards, and hence the funding deficit. As a result, tax-deductible mandatory contributions also decrease, which ceteris paribus, should increase the tax liability assuming the firm only contributes the required amount.

Prior to MAP-21, as outlined in the Pension Protection Act of 2006 (PPA), discount rates were based on a 24-month average of investment grade corporate bond yields. The law effectively raised discount rates by changing the 24-*month* average to a 25-*year* average. Given the historically low interest rate environment following the financial crisis of 2008–2009, the 25-year average corporate bond yields were considerably higher than the 24-

[3] Additional details on the legislation and funding projections can be found at https://www.fhwa.dot.gov/map21/

[4] See the following link for CBO projections on MAP-21 budget implications https://www.cbo.gov/sites/default/files/cbofiles/attachments/hr4348conference.pdf

month average yields. The published rates instituted are based on a window around the 25-year average rate and are 120-348 basis points higher.[5] If the corporate bond rate for any month does not fall within a 90-110% window of the 25-year average for that month, the minimum (maximum) rate used will be the 90% (110%) value of the 25-year average rate. The law in its original form intended for the window to widen, yet subsequent legislation has instituted the 90-110% window through 2020.

The discount rates used to determine the value of the liability are divided into three "segment rates." The segments are based on the expected timing of payable benefits and are divided into periods of zero-to-five years, five-to-twenty years, and greater than twenty years. The segment rates are published by the IRS on a monthly basis for the use of single-employer corporate DB pensions.[6] Figure 2.1 shows the equally-weighted average segment rates prior to and after the legislation took effect. Plans incorporate the published rate into actuarial estimates based on the plan year. The effective interest rate to discount future benefit payments will vary based on the demographics of plan participants. Consider a hypothetical firm with a young workforce that is entirely under the age of 40. Based on an average expected retirement age of 60+, the entire value of expected benefits would be discounted using the third segment rate. In this extreme scenario, the third segment rate would be equivalent to the effective interest rate. Naturally, the workforce will be far more diverse for the average firm and the impact of a particular segment rate on present value calculations will vary accordingly.

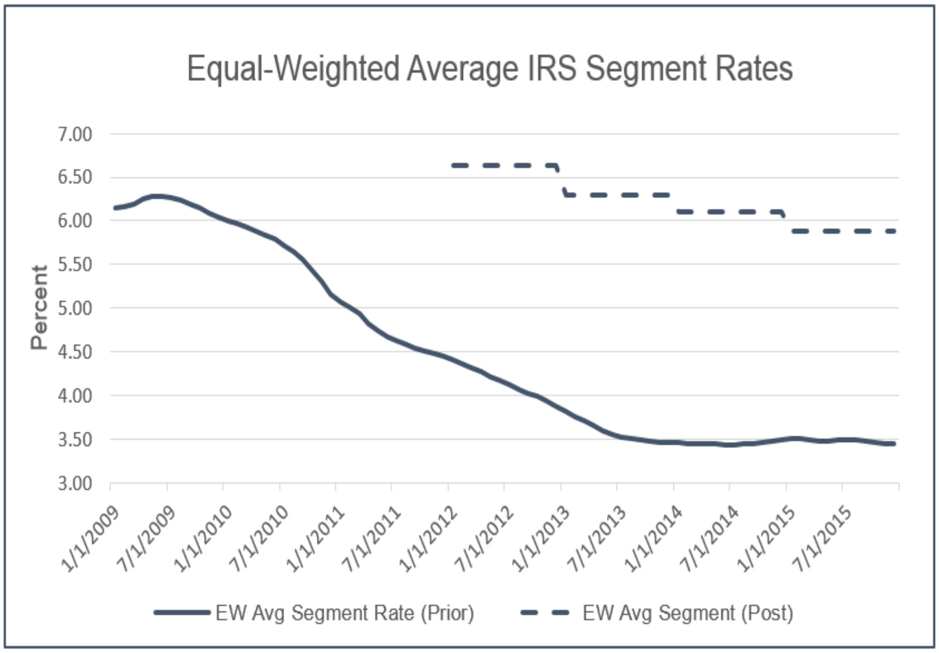
The changes to discount rates affect all firms in our sample, albeit not identically due to the noted demographic differences among workforces across firms. However, all three segment rates increased with the introduction of 25-year averages. Pension funding status, in large part due to the negative shock to pension liabilities, experiences a 14% increase from 2011 to 2012 for the average firm in the sample. Figure 2.2 shows a kernel density

[5] https://www.irs.gov/pub/irs-drop/n-12-55.pdf

[6] IRS minimum present value segment rates are published at https://www.irs.gov/retirement-plans/minimum-present-value-segment-rates

Figure 2.1: Average Discount Rates

This figure shows the equally-weighted average discount rates prior to and after the MAP-21 legislation took effect. The solid line represents the unadjusted rate, while the dashed line provides the adjusted rate based on average 25-year investment grade corporate bond yields. Data is available directly through IRS website.

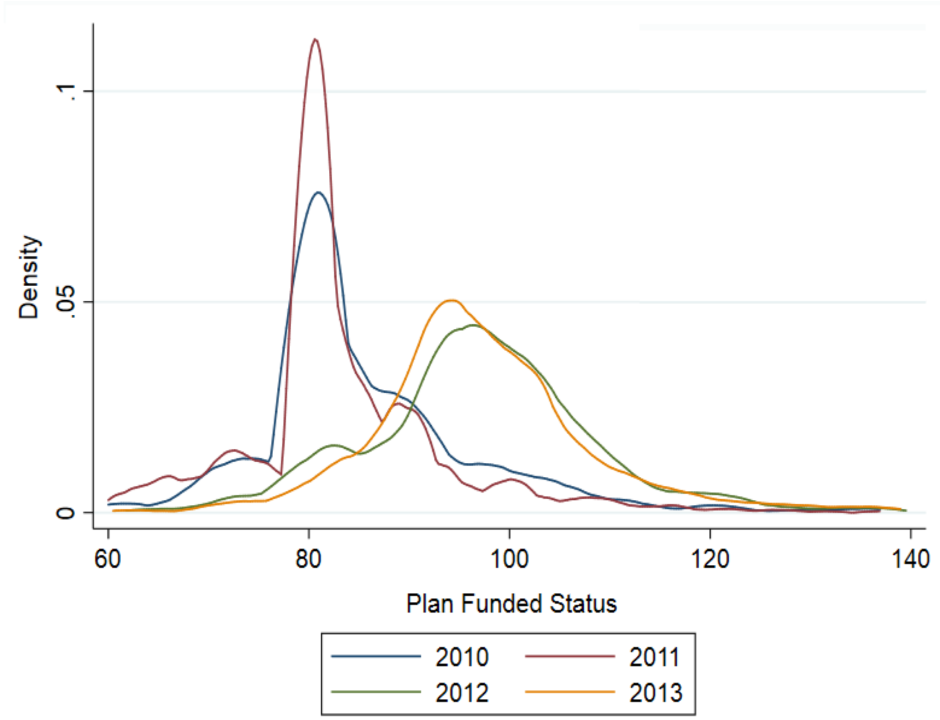


estimate of funded status prior to (2010-2011) and after (2012-2013) the shock to discount rates. A Kolmogorov-Smirnov test confirms these distributions are significantly different from each other (p-value of 0.00). In no other year in the sample does the average change by more than 5.6%. We exploit this plausibly exogenous shock to the pension liability in developing a causal argument for the effects of pension overhang on corporate investment policy. [48] uses a similar methodology to investigate the cash flow effects of pension policy on corporate payouts and cash holdings. In contrast to our main result, he does not find an effect on firm investment.

MAP-21 institutes a change in the discount rates used to measure the pension liability. It does not reduce the total disbursements owed to pension beneficiaries in retirement. The appropriate discount rate for pension liabilities is a topic of debate both in practice and academic literature. The cash flow stream to pensioners should be discounted at a rate that reflects the economic value of the claim ([52]). [53] suggest the Treasury yield curve as the

Figure 2.2: Plan Funded Status - Pre and Post

This figure shows a kernel density plot of plan funded status both prior to (2010-2011) and after (2012-2013) the effects of higher discount rates imposed by MAP-21

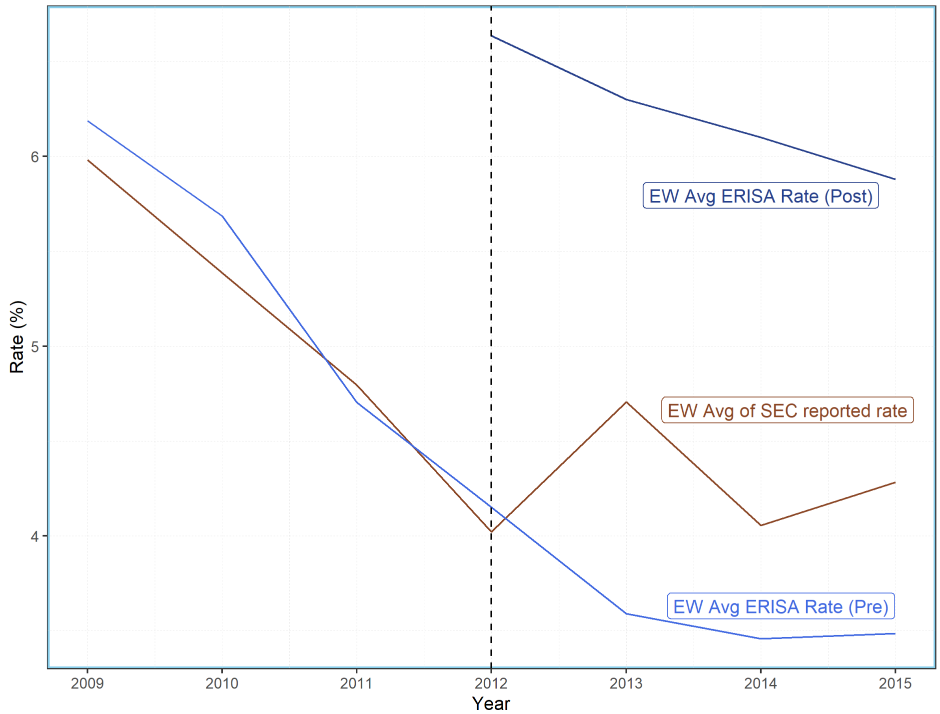


appropriate benchmark for public entities given the protections granted to state employees. In the case of corporate pension plans, the use of historical market prices of unsecured debt obligations appears reasonable. The appropriate historical timeframe to measure these yields warrants consideration due to the long-term nature of future pension obligations and the variability of investment grade bond yields over time. Furthermore, the PBGC will assume payment up to certain thresholds should the firm fall short in a bankruptcy scenario. A debate on the appropriate discount rate is beyond the scope of this paper. Nevertheless, companies do appear to change the pension discount rate disclosed in their SEC filings in response to MAP-21.

Figure 2.3 shows the equal-weighted average ERISA discount rate pre and post MAP-21 and the equal-weighted average discount rate disclosed by our sample of firms in their SEC filings. The former rate is the one directly affected by the law, while the latter one is set by the firm with some discretion. Figure 2.3 shows a sharp increase in the discount

Figure 2.3: SEC vs. ERISA Rates

This figure shows the equal-weighted average ERISA discount rates prior to and after the MAP-21 legislation as well as the equal-weighted average discount rate disclosed by firms in their 10-K filings.



rate companies disclose to the SEC after MAP-21 is enacted; prior to the law change, the SEC rate tracks the ERISA rate very closely. In the year following the law change, the spread between the SEC reported discount rate and the prior ERISA-mandated rate is over 75 basis points. As previously discussed, the ERISA rate prior to MAP-21 is based on the 24-month benchmark of investment grade corporate yields and continues to fall after 2012 suggesting the SEC rates are not responding to prevailing market rates. Furthermore, after the spread narrows in 2014, it widens again in 2015. Additional legislation was passed in late 2014 extending the funding rules instituted by MAP-21. This evidence is consistent with companies adjusting their pension discount rate after MAP-21.

2.2.3 Pension Overhang Measure, Identification Strategy & Empirical Specification

In this section, we first present the details of the construction of our pension overhang measure that augments the debt overhang measure used in [40] and [43]. We then discuss our identification strategy using our new pension overhang measure and the associated empirical specification.

The pension overhang correction term represents the firm value to pensioners in the case of a default scenario. We develop a measure to proxy for the overhang effects stemming from DB plan deficits utilizing the basic construct of the debt overhang correction term of [40] and revisited by [43], [54]:

$$Debt\ Overhang^{hlw} = \frac{D_t}{K_t} * RecoveryRate * \left[\sum_{s=1}^{20} \omega_{t+s}^{Moodys}[1 - 0.05(s-1)] \times r_{t+s}\right] \quad (2.1)$$

where $\frac{D_t}{K_t}$ represents the ratio of long-term debt to capital stock, the $Recovery\ Rate$ is the recovery to debtholders by industry as in [55] and ω_{t+s} represents the Moody's probability of default at time t, s years into the future.

To estimate the incremental effect of pension debt overhang, we construct a measure, *Pension Overhang*,

$$PensionOverhang_{i,t} = \frac{PenDeficit_{i,t}}{K_{i,t}} * RecoveryRate * \left[\sum_{s=1}^{20} \omega_{t+s}^{Moodys}[1 - 0.05(s-1)] \times r_{t+s}\right] \quad (2.2)$$

where

$$PenDeficit_{i,t} = (1 - WAFS_{i,t}) * PL_{i,t} \quad (2.3)$$

and

$$WAFS_{i,t} = \sum_j FS_{j,t} * \frac{PL_{j,t}}{PL_{i,t}} \quad (2.4)$$

in which PL denotes the pension liability for either firm (i) or plan (j). $WAFS_{i,t}$ is the firm-level weighted-average funded status (WAFS). For each year, the funded status of each plan, $FS_{j,t}$, is scaled according to the plan liability's contribution to the total firm U.S. pension liability. The equation follows HLW with the exception of replacing long term debt with the unfunded portion of the pension liability. We continue to assume a 5% amortization of the pension liability each year, consistent with the long-duration nature of pension obligations and required period to contribute toward pension deficits.[7] For example, if a particular sponsor had a single pension plan funded with assets equivalent to 80% of its ABO of \$100 million, the $PenDeficit$ would be \$20 million. The $PenDeficit$ variable is decreasing in firm WAFS and increasing in the total pension liability.

The funded status of each plan is weighted such that a smaller plan (by liability) with a high funded status would not have the same impact on $WAFS_{i,t}$ as a larger plan with a lower funded status. Unlike the debt overhang variable, $Pension\ Overhang$ can appear as a negative value and indeed will be negative for a firm with a WAFS above 100%. In the case of default or plan termination, if a plan is overfunded, the residual value (after payments to beneficiaries) reverts to the firm. It is therefore feasible to have a "negative" overhang with respect to the pension liability.[8]

We examine the impact of an exogenous shock to the pension funding liability on firm investment policy through a difference-in-differences framework. Prior to the law change, we identify firms which may experience overhang effects from their unfunded pension liability, where the unfunded portion is a function of the weighted-average pension funded status and the total pension liability. Firms that are most encumbered by pension debt would be expected to experience the greatest overhang relief from the changes mandated by MAP-21. Near term cash flows generated by higher investment would accrue to shareholders at a higher rate at the expense of lower pension contributions. In our primary specification, we regress annual investment scaled by lagged capital stock on the interaction term of $HighPenOverhang$ and $Post$ along with a series of controls which may impact investment policy,

$$\begin{aligned}\frac{I_{i,t}}{K_{i,t-1}} = \alpha_i + \eta_t + \beta_1(HighPenOverhang_i \times Post) + \beta_2 Q_{i,t-1} + \beta_3 \frac{CF_{i,t}}{K_{i,t-1}} \\ + \beta_4 Overhang^{HLW}_{i,t} + \beta_5 Contributions_{i,t} + \epsilon_{i,t}\end{aligned} \tag{2.5}$$

[7] Average duration of approximately 13-years as estimated by Towers Watson for 418 corporate pensions during the middle of our sample period.

[8] Prior evidence reveals how firms (particularly those more financially constrained) have tapped overfunded pensions transferring benefits from workers to shareholders ([23])

where the coefficient on the interaction between $HighPenOverhang$ and $Post$, β_1, is of primary interest. $Post$ is an indicator equal to one for all years in the sample after MAP-21 took effect. We separate the sample based on the median value of the pension overhang variable and denote $HighPenOverhang$ firms as those falling above the median in 2011, the year prior to the law change.[9] We control for variables correlated with the investment opportunity set or which may suggest the firm is financially constrained including Tobin's Q, cash flow, and the HLW measure of debt overhang. In the full specification, we also control for the annual pension contributions. We want to ensure our results are not driven by an internal cash constraint alleviated by the lower pension contributions related to MAP-21. If the unfunded pension liability exerts overhang effects incremental to those of long-term debt, a higher value of pension debt overhang should serve as a hindrance to firm investment.

Figure 2.4 displays the evolution of both the debt overhang and pension overhang variables throughout the sample period. The pension overhang variable experiences a dramatic drop from 2011 to 2012 consistent with higher discount rates, and a lower pension liability due to the implementation of MAP-21.[10] Firms were given the option to elect into the discount rates mandated by MAP-21 in either plan year 2012 or 2013. Delayed adoption coupled with strong returns on invested pension assets during the post period aid in explaining the incremental fall in $Pension\ Overhang$ relative to debt overhang.

The causal effect of the results rests on the assumption that the legally mandated change to interest rates is not disproportionately correlated with the investment opportunity set of firms experiencing high pension debt overhang. MAP-21 was intended to reauthorize spending for U.S. transportation infrastructure, while the changes to pension calculations were a source of offsetting revenue. Additionally, the law change impacts all firms, yet in a

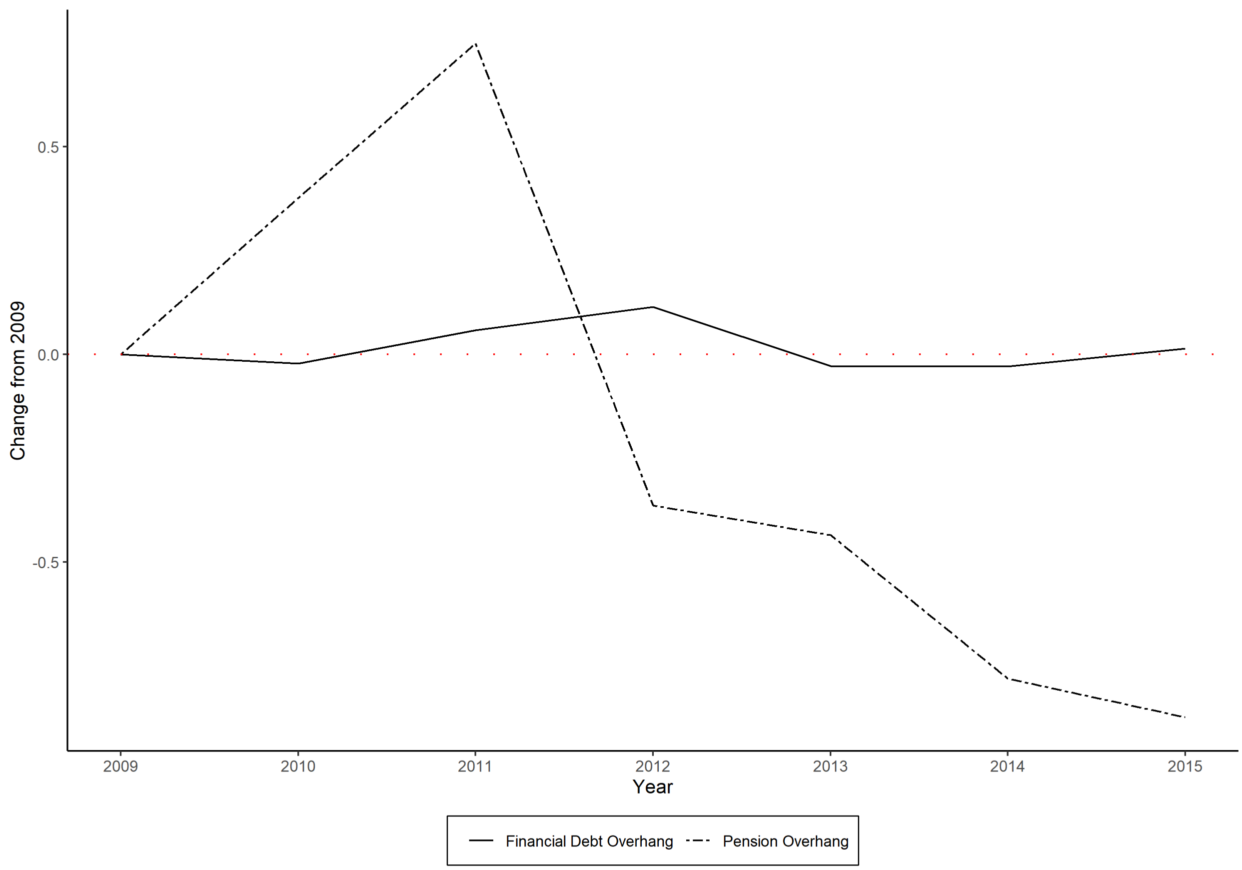
[9]As robustness, in Table B.5, for purposes of calculating $HighPenOverhang$, we redefine the period prior to MAP-21 as 2009-2011 to ensure the main result is not driven solely by activity that may have occurred in 2011.

[10]Increases in the pension overhang measure from 2009-2011 can be attributed to a dramatic decrease in discount rates as well as negative equity returns following the financial crisis

Figure 2.4: Overhang Variables

This figure documents the change in overhang variables across the sample period. To note, the pension overhang variable is constructed so that it can take negative values, unlike the traditional debt overhang measure. Financial debt overhang is constructed following Hennessy, Levy, Whited (2007). Pension Overhang is constructed as

$$Pension\ Overhang_{i,t} = \frac{Pension\ Deficit_{i,t}}{K_t} * Recovery\ Rate * \left[\sum_{s=1}^{20} \omega_{t+s}^{Moodys} [1 - 0.05(s-1)] \times r_{t+s}\right]$$



heterogeneous manner based on a firm's exposure to each of the three segment rates. MAP-21 redefines the segment rates based on a 25-year historical average of high grade corporate bond yields based on pre-defined maturities. While segment rates would have marginally differential effects based on pension beneficiary demographics, we see it as unlikely the universal nature of the law change was intended to impact firms with specific workforce demographics which are correlated with historical interest rates. Nonetheless, perhaps the effect may be unintended yet a correlation remains. For example, if the decrease in the pension liability disproportionately provided opportunities for firms in certain high growth industries, they would be expected to increase investment after the passage of MAP-21 exclusive of the law. We address this possibility in the main empirical specification by controlling for industry times year fixed effects.

Based on the dynamic impact of MAP-21, higher firm investment may be driven by other channels aside from debt overhang, but that are affected by a reduction in the pension liability. Motivated by prior research, we explore two of these potential channels in the empirical analysis—internal cash constraints and marginal tax rates. First, mandatory pension contributions decrease, which may relieve cash flow constraints on the firm. [12] shows that contributions may indeed affect investment. Yet, in a subsequent analysis, [13] find support for cash flow implications of mandatory contributions with respect to R&D spending, inventories, receivables, and employment, but no effect on capital expenditures. The authors point out the relatively small size of mandatory contributions relative to total assets is unlikely to have a significant impact on investment policy. Similarly, we observe that mandatory contributions only account for 1% of total cash flows based on the median of our sample - a fraction unlikely to materially impact cash flow intensive firm policies such as investment. [15] and [56] find evidence that firms with underfunded plans are overvalued and under-invest offering a cash flow explanation for their findings. The evidence we present in this paper is consistent with these prior results, yet provides support for the pension debt overhang channel in driving the negative effects on investment.

Second, the effect on taxable income, due to lower tax-deductible contributions, may encourage firms to seek alternative tax shelters. Investment may then increase for the sake of deducting depreciation expense. Firms with the highest marginal tax rates would be expected to experience the largest impact from lower pension contributions. Although mandatory contributions will decrease as a result of MAP-21, firms may still make voluntary pension contributions which remain tax-deductible up to a threshold well in excess of full funding. This option could attenuate the incentives for a firm to seek additional shelters for taxable income. In the empirical analysis that follows, we do not find support that either of these factors are driving the changes to corporate investment policy.

2.3 Data and Summary Statistics

We use IRS Form 5500 filings from 2009 through 2015 as the primary source of DB pension plan data. These forms are submitted annually, at the plan level, by sponsors of U.S. pension plans. We utilize the detailed information provided on firm assets and liabilities, firm contributions to plans, and discount rates. The sample is restricted to single-employer DB plans and on the ability to merge with Compustat by employer identification number (EIN).[11] If the Form 5500 data cannot be matched to a Compustat EIN it is dropped from the sample. All individual plan level data are aggregated at the firm-year level.

2.3.1 Sample Selection

Pension information from SEC filings are not used due to various shortcomings specific to this data and consistent with those documented in prior literature. Generally accepted accounting principles (GAAP) allow for far greater leniency in actuarial assumptions relative to those required by the IRC. The change in discount rates mandated by MAP-21 would not be directly applicable to GAAP standards. Plan funded status, mandatory pension contributions, and related penalties are enforced by the IRS based on ERISA and IRC standards as opposed to GAAP. Based on the sources used, international pension data is not included in our analysis.

The remaining sample consists of 3,424 firm-year observations for 588 unique firms after removing financials, and firms with negative or missing total assets, sales, or capital stock. Based on the sample, the Form 5500 data accounts for approximately 60% of total pension liabilities reported on SEC form 10-K. Non-U.S. pension plans, small plans, an

[11] We supplement with manual matching for certain plans where we can identify the parent company

inability to match on EIN and differences in pension accounting between IRS and SEC documents account for the remainder.

Table 2.1 provides descriptive statistics on the complete sample. Relative to the Compustat universe, firms sponsoring DB plans are larger, have higher total leverage and higher cash flow. These discrepancies are consistent with the nature of a typical DB pension plan sponsor—older, industrial firms that are part of industries characterized by high tangibility (manufacturing, auto, etc.). Panel A provides descriptive statistics on key firm-level variables, while Panel B reports statistics specific to pension characteristics. Both panels are then further divided into three columns including the full sample and then by high versus low pension overhang firms denoted by above or below median. High pension overhang firms are characterized by an above median unfunded pension liability.

High pension overhang firms are generally smaller, have higher leverage, and pension liabilities comprise a larger share of total assets - indications that as a group, these firms may face greater financial constraints. The average plan in the sample has over 14,000 participants of which most are already in retirement (33% active participants on average). The average firm in our sample sponsors three distinct defined benefit pension plans.

2.4 Empirical Results

We explore two primary questions in this section: (1) does the overhang stemming from the pension deficit have an incremental impact on investment after controlling for Tobin's Q, cash flow, and HLW debt overhang and (2) does the reduction in the pension liability resulting from MAP-21 encourage firm investment? We first document the incremental impact that the pension overhang variable has on investment in a panel regression framework. We then extend the analysis to a difference-in-differences estimation to examine the impact of MAP-21 on firms with a higher degree of pension overhang prior to MAP-21. We further explore the impact on long-term credit ratings, cross-sectional results for financially constrained firms and differences in managerial incentives, and alternative explanations which

Table 2.1: **Summary Statistics**

Table 2.1 provides summary statistics for the 3,461 firm-year observations for 590 unique firms. Inclusion in the final dataset results from the intersection of the Compustat database and IRS Form 5500 data. Financial firms (SIC 6000-6799) and utilities (SIC 4900-4999) are excluded. Panel A describes variables solely based on data available in the Compustat dataset. Panel B provides characteristics of pension variables as reported by Form 5500 filings and associated schedules. Firm level presents aggregated information in the case firms have multiple defined benefit plans. Plan level presents statistics based on a disaggregated basis. Results for the full sample are shown alongside the split sample based on the above (high) or below (low) median measure of pension overhang prior to the onset of MAP-21.

Panel A — **Compustat Variables**

	Full Sample				**High Pension Overhang**				**Low Pension Overhang**			
	Mean	Med	SD	N	Mean	Med	SD	N	Mean	Med	SD	N
Assets - Total (mm)	12,921	3,005	30,236	3424	11,222	3,590	25,146	1022	25,067	8,866	41,325	1022
Cash/Assets	0.10	0.08	0.08	3423	0.10	0.08	0.08	1022	0.09	0.07	0.07	1022
Liab/Assets	0.64	0.60	0.24	3414	0.75	0.71	0.23	1019	0.63	0.60	0.19	1022
Debt/Assets	0.25	0.22	0.20	3410	0.32	0.27	0.21	1019	0.27	0.25	0.17	1022
Tobin's Q	1.64	1.46	0.72	3210	1.53	1.39	0.53	919	1.83	1.61	0.82	993
EBITDA/Sales	0.15	0.14	0.10	3424	0.14	0.13	0.08	1022	0.19	0.18	0.11	1022
Capex/Assets	0.04	0.03	0.04	3424	0.03	0.03	0.03	1022	0.05	0.04	0.04	1022
Capex/K_{t-1}	0.18	0.16	0.10	3424	0.18	0.16	0.09	1022	0.19	0.18	0.09	1022
R&D/Assets	0.02	0.02	0.02	2279	0.02	0.02	0.02	738	0.02	0.01	0.03	684

Panel B — **Pension Variables**

Firm level

	Full Sample				**High Pension Overhang**				**Low Pension Overhang**			
	Mean	Med	SD	N	Mean	Med	SD	N	Mean	Med	SD	N
Participants/Tot Emp	1.07	0.78	1.16	3360	1.30	1.02	1.15	1001	0.73	0.60	0.77	1016
Pen Liab/Tot Assets	0.15	0.09	0.17	3422	0.21	0.16	0.18	1022	0.08	0.04	0.10	1022
Pen Assets/Tot Assets	0.15	0.10	0.17	3417	0.21	0.16	0.19	1021	0.09	0.05	0.11	1020
Mand Cont/Tot Assets	0.004	0.002	0.01	3424	0.01	0.003	0.01	1022	0.002	0.001	0.003	1022
Mand Cont/EBITDA	0.04	0.01	0.08	3423	0.05	0.02	0.07	1022	0.01	0.004	0.03	1022
Wtd Avg Funded Status	93.30	92.88	14.68	3424	90.25	90.39	12.23	1022	96.71	95.58	15.58	1022

Plan level

	Mean	Med	SD	N	Mean	Med	SD	N	Mean	Med	SD	N
Funded Status	97.18	94.33	35.85	5233	91.19	92.13	14.71	1838	103.98	97.03	46.17	1677
Discount Rate	5.96	6.00	0.51	5136	5.98	6.00	0.50	1809	5.95	6.00	0.52	1609
Eff Interest Rate	6.58	6.42	9.17	5233	6.45	6.42	0.39	1837	6.46	6.42	0.44	1677
Avg Retirement Age	62.45	63	2.62	5085	62.14	62	3.73	1790	62.24	62	1.66	1583
Total Participants	14,710	2,507	43,967	5234	20,059	4,830	47,347	1838	16,540	2,747	46,465	1677
Active Part %	0.33	0.31	0.23	5200	0.28	0.25	0.20	1814	0.37	0.38	0.23	1673
Plans per Firm	3.26	2	3.65	5234	3.78	3	3.26	1838	4.07	2	5.03	1677

may be driving our results.

2.4.1 Pension Overhang and Investment

We begin by examining the nonparametric relationship between investment and the WAFS of the firm in Figure Figure 2.5. [12] produces similar estimates in describing the relationship between funded status and investment.[12] The figures reveal a striking resemblance despite the sample periods differing by more than a decade. It appears the positive relationship between funded status and scaled investment is persistent across time. Likewise, we find the relationship levels off as the plan nears 100% funded. Given the noted concerns with the causal impact of mandatory pension contributions, our ensuing analysis seeks to shed further light on the channel which may be driving the relationship between investment and funded status.

Table 2.2 reports the estimates from a fixed effects model controlling for Tobin's Q, cash flow scaled by capital stock, and financial overhang following HLW. The table shows the incremental impact of each factor on investment. Coefficients for the stated variables are in line with prior results presented in the overhang literature.[13] The number of observations decreases in columns (2)-(6) as our calculation of the overhang variable excludes non-rated firms.[14] The average firm in our sample is rated BBB. To the extent the average of non-rated firms carry an average credit rating below BBB, our results may provide a conservative estimate as lower rated firms would be expected to experience a higher overhang effect. Most notably, column (3) includes the variable of interest, $Pension\ Overhang$. The overhang effect attributable to the funding deficit has a negative and statistically significant impact on firm investment. A one standard deviation increase in pension overhang suggests an approximate 1% percentage point decrease in investment to capital stock. This

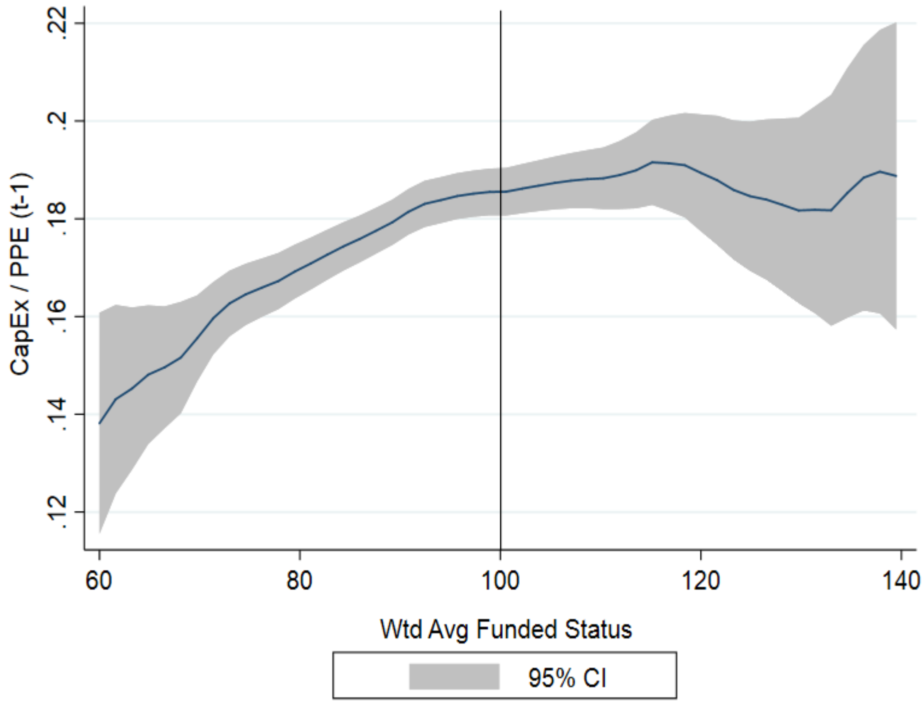
[12]Consistent evidence reproduced by Bakke and Whited (2012)

[13]The R^2 of our regressions is lower than that of [57], who show that the empirical fit of q investment regressions has increased in recent years due to the emergence of high-tech firms; however, less than 15% of our sample is comprised of high-tech firms.

[14]In untabulated results we follow [58] in imputing bond ratings and find consistent results.

Figure 2.5: Capital Expenditures by Funded Status

This figure shows the results of a kernel regression using the Epanechnikov kernel. Results are from a pooled regression. 95% confidence intervals are designated by the shaded region. The y-axis is capital expenditures scaled by lagged capital stock. The x-axis is the weighted-average funded status for the all firm pension plans.



equates to a 5.5% change in investment. For reference, column (2) shows a one standard deviation increase in the HLW debt overhang measure is associated with an approximate 6.6% decrease in investment. Table Table B.2 in the Internet Appendix provides pairwise correlations of the variables used in the regression. We would expect a meaningful overlap between debt overhang and the pension overhang variables given numerous common inputs, yet the correlaton of 0.30 suggests the pension overhang variable captures sufficiently different variation.

The coefficient on the overhang measure in column (2) does not have a statistically significant impact on investment. The sample is restricted to firms with a defined benefit pension plan that have a credit rating—generally larger, mature firms, with greater access to capital markets. We would expect these firms to be less sensitive to the debt overhang correction term when the pension liability is excluded. [50] suggest firms do consider the

Table 2.2: **Incremental Effect of Pension Overhang**

This table is a regression of capital expenditures scaled by lagged capital stock on $Tobin's\ Q$, $Cash\ flow$, $Overhang$, $Employer\ Contributions$ and the novel measure of pension overhang, $Pension\ Overhang$. Tobin's Q is the market value of equity plus the book value of debt divided by the book value of assets. Tobin's Q is lagged one year. The cash flow variable is constructed following [12] to account for non-cash pension expense. Cash flow is scaled by lagged capital stock. Low (High) Overhang is an indicator variable equal to 1 if the firm-year is in the lower (top) tercile of Overhang. Employer contributions are reported in plan Form 5500 filings and aggregated to the firm level.

	(1) Capex/PPE$_{t-1}$	(2) Capex/PPE$_{t-1}$	(3) Capex/PPE$_{t-1}$	(4) Capex/PPE$_{t-1}$	(5) Capex/PPE$_{t-1}$	(6) Capex/PPE$_{t-1}$
Tobin's Q	0.050***	0.056***	0.057***	0.056***	0.056***	0.056***
	(7.382)	(7.729)	(7.923)	(7.811)	(7.797)	(7.795)
Cash flow	0.025***	0.020***	0.019***	0.018***	0.020***	0.020***
	(3.730)	(2.748)	(2.761)	(2.599)	(2.839)	(2.831)
Overhang		−0.086		−0.071		
		(−1.364)		(−1.116)		
Low Overhang					−0.005	−0.005
					(−0.752)	(−0.755)
High Overhang					−0.017**	−0.017**
					(−2.162)	(−2.143)
Pension Overhang			−1.009***	−0.936***	−0.955***	−0.974***
			(−4.037)	(−3.479)	(−3.761)	(−3.745)
Employer Contributions						0.012
						(0.180)
Firm	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3,190	1,964	1,967	1,964	1,964	1,964
Within R^2	0.14	0.19	0.20	0.20	0.20	0.20
Adj. R^2	0.59	0.65	0.65	0.66	0.66	0.66

Clustering for standard errors at the firm-level for all specifications.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

pension liability in maximizing the capital structure of the firm. In column (5) we separate HLW debt overhang into terciles and find a significant negative effect on investment driven by those firms in the tercile experiencing the highest degree of debt overhang. The middle tercile is omitted in the regressions. The magnitude of the coefficient suggests these firms experience a 1.7 percentage point lower level of investment to capital stock or approximately a 10% lower rate of investment.

Lastly, in column (6), we include mandatory firm cash contributions to pension plans, scaled by lagged capital stock, as an explanatory variable in the regressions. The coefficient on the $Pension\ Overhang$ variable remains significant and little changed after controlling for cash contributions. If investment policy is impacted through an internal cash flow channel we would expect to see higher cash contributions to negatively impact capital expenditure spending. This is not the case. The economic magnitude of the coefficient on $Pension\ Overhang$ remains largely unchanged across specifications. The immaterial effect of cash contributions on investment is consistent with the results documented by [48] and [13]. The null result may be due to the relatively small magnitude of annual contributions relative to firm size or because firms have the optionality to contribute above the mandatory minimum in any given year and credit such contributions to future years' required contributions. In untabulated results, we substitute total employer contributions for the annual mandatory minimum—the coefficient is insignificant while remaining effects are left largely unchanged. Furthermore, it is possible our estimate of the underinvestment effect caused by pension overhang may be affected by measurement errors in Q. We address this issue by using the high-order cumulant equations estimator of [59]. Our main results are largely consistent and are reported in the Internet Appendix.

Table 2.3 tests the impact of MAP-21 on the underinvestment caused by pension overhang. As mentioned above, MAP-21 brought relief to companies with a high pension overhang, and given the findings in Table 2.2 we expect to see an increase in investment by these companies. We test this implication in a difference-in-differences framework according to equation Equation 2.5.

Table 2.3: **Difference-in-Differences - Pension Overhang and MAP-21**

This table presents a difference-in-differences analysis of capital expenditures scaled by lagged capital stock:

$$\frac{I_{i,t}}{K_{i,t-1}} = \alpha_i + \eta_t + \beta_1 (High\,Overhang \times Post) + \beta_2 Q_{i,t-1} + \beta_3 \frac{CF_{i,t}}{K_{i,t-1}} + \beta_4 Overhang_{i,t} + \beta_5 Contributions_{i,t} + \epsilon_{i,t}$$

$HighPenOverhang$ is an indicator variable that takes the value of 1 if a firm falls above the median $Pension\ Overhang$ in the year prior to MAP-21. $Post$ is an indicator variable for all years after the passage of the legislation (2012). $Underfunded$ is an indicator equal to 1 if a firm's WAFS was under 100% in the year prior to MAP-21. We control for $Tobin's\ Q$, $Cashflow$, $Overhang$, $EmployerContributions$. Tobin's Q is the market value of equity plus the book value of debt divided by the book value of assets. Tobin's Q is lagged one year. The cash flow variable is constructed following [12] to account for non-cash pension expense. Cash flow is scaled by lagged capital stock. Employer contributions are reported in plan Form 5500 filings and aggregated to the firm level.

	(1) Capex/PPE$_{t-1}$	(2) Capex/PPE$_{t-1}$	(3) Capex/PPE$_{t-1}$
HighPenOverhang × Post	0.024***	0.024***	
	(3.345)	(3.453)	
Underfunded × Post			0.013
			(0.937)
Tobin's Q	0.058***	0.051***	0.057***
	(8.055)	(7.071)	(7.743)
Cash flow	0.018**	0.025***	0.020***
	(2.523)	(3.425)	(2.816)
Overhang	−0.088	−0.083	−0.092
	(−1.477)	(−1.403)	(−1.526)
Employer Contributions	−0.035	0.070	−0.057
	(−0.605)	(1.060)	(−0.973)
Firm	Yes	Yes	Yes
Year	Yes	No	Yes
Industry × Year	No	Yes	No
Observations	1,873	1,873	1,910
Within R^2	0.21	0.17	0.19
Adj. R^2	0.66	0.64	0.66

Clustering for standard errors at the firm-level for all specifications.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

We leverage the same control variables shown in Table 2.2. We control for cash contributions, which may have been alleviated by an increase in funded status. We identify firms as "High Pension Overhang" if they fall above the median of $Pension\ Overhang$ in 2011, the year prior to the passage of MAP-21. The main specification is in column (1) where a dummy for $HighPenOverhang$ is interacted with a dummy for $Post$, an indicator for all years in the sample after the law was passed and higher discount rates took effect.[15] The coefficient on β_1 indicates that high pension overhang firms increase investment by 2.4 percentage points after the passage of MAP-21, which equates to a 13% change relative to investment levels prior to the law. Column (2) includes industry times year fixed effects. If certain industries benefited to a relatively greater extent then the results may not be driven by higher discount rates. The effects on investment are largely unchanged and remain highly significant.

Similar to $HighPenOverhang$, in column (3), we use an indicator variable for all firms which have a funded status below 100%. Our finding is not being driven by the firms with underfunded pensions as a whole, but rather those which experience a higher degree of pension overhang. Both the funded status of the firm as well as the size of the total pension liability should play a role in firm policy. Both of these factors are accounted for in our measure of pension overhang. The direction and magnitude of coefficients on all controls remain largely unchanged across specifications. To ensure our measure is robust, we perform the same difference-in-difference regressions, but scale by total firm assets. Consistent, significant results are shown in the Appendix.

Table 2.4 shows the investment behavior of above median overhang firms by year. In this table we regress $HighPenOverhang$ on year dummies for each year in the sample omitting 2009. Column (1) excludes control variables while column (2) includes the full set of independent variables used in the prior analysis. We find no material differential impact on investment up to and including 2012, the year in which MAP-21 was passed.

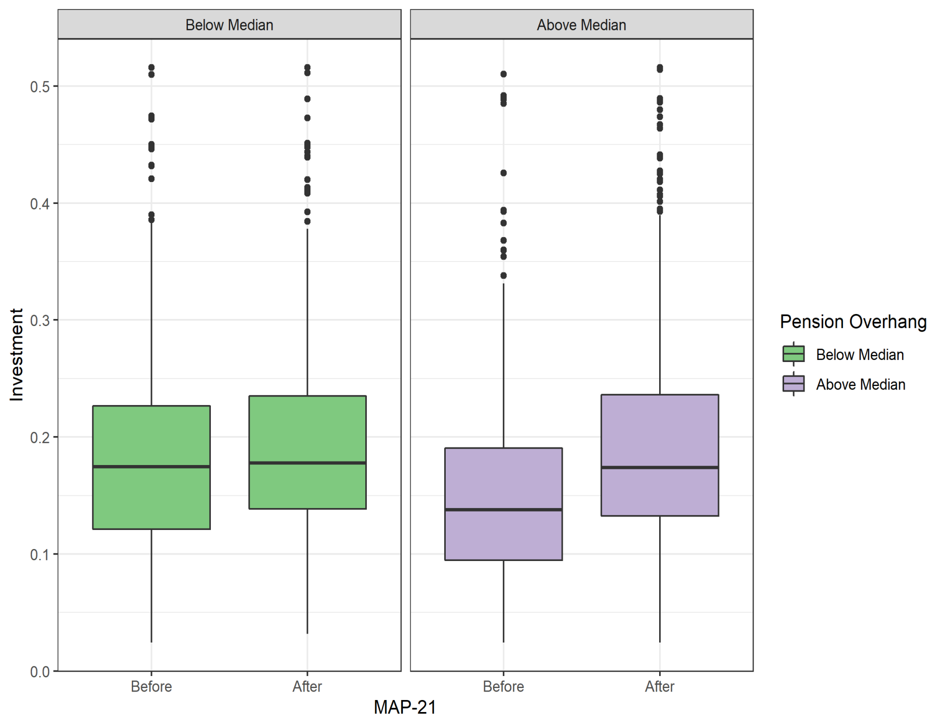
[15] We conservatively define post to include calendar year 2012. The law was first introduced to Congress in early 2012 at which point firms may have anticipated the passing and increased capital investment in the 2nd-4th quarters. Alternatively, investment may respond with a lag. In untabulated results, we define $Post$ as beginning in calendar year 2013 and the results are economically and statistically stronger.

The impact in years 2013-2015 indicate a substantial increase in investment for firms which were ex ante exposed to the greatest pension overhang effects.

Figure 2.6 displays a boxplot for the distribution of investment for below and above median overhang firms both prior to and after the passage of MAP-21. Below median overhang firms exhibit minimal change, the median investment rate for this group barely budged after the law; on the other hand, above median overhang firms exhibit a sharp shift up in their investment distribution in the post period. This evidence is consistent with high overhang firms responding to the pension relief created by MAP-21.

Figure 2.6: Distribution by Median Overhang

This figure shows a boxplot of the distribution of investment for below and above median pension overhang firms both before and after MAP-21.



2.4.2 Matching Analysis

Table 2.1 shows that the low and high pension overhang firms differ in characteristics such as Tobin's Q and total assets. The difference-in-difference estimator is robust to these variations as long as they don't correlate with the MAP-21 event. Nevertheless, we

Table 2.4: **High Pension Overhang and Investment—Year Indicators**

This table presents a test of the parallel trends assumption. The regression estimates the impact of high pension overhang on capital expenditures by year. $HighPenOverhang$ is an indicator variable that takes the value of 1 if a firm falls above the median $Pension\ Overhang$ in the year prior to MAP-21. We control for $Tobin's\ Q$, $Cashflow$, $Overhang$, $Employer\ Contributions$. Tobin's Q is the market value of equity plus the book value of debt divided by the book value of assets. Tobin's Q is lagged one year. The cash flow variable is constructed following [12] to account for non-cash pension expense. Cash flow is scaled by lagged capital stock. Employer contributions are reported in plan Form 5500 filings and aggregated to the firm level.

	(1) Capex/PPE$_{t-1}$	(2) Capex/PPE$_{t-1}$
HighPenOverhang × Year 2010	0.004	−0.009
	(0.506)	(−1.114)
HighPenOverhang × Year 2011	0.010	0.000
	(1.038)	(0.007)
HighPenOverhang × Year 2012	0.015	0.005
	(1.382)	(0.467)
HighPenOverhang × Year 2013	0.034***	0.020*
	(3.245)	(1.869)
HighPenOverhang × Year 2014	0.040***	0.025**
	(3.271)	(2.043)
HighPenOverhang × Year 2015	0.049***	0.037***
	(4.164)	(3.284)
Tobin's Q		0.058***
		(8.174)
Cash flow		0.018**
		(2.551)
Overhang		−0.087
		(−1.473)
Employer Contributions		−0.018
		(−0.297)
Firm	Yes	Yes
Year	Yes	Yes
Observations	2,044	1,873
Within R^2	0.11	0.21
Adj. R^2	0.61	0.66

Clustering for standard errors at the firm-level for all specifications.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

investigate if controlling for sample characteristics changes our results.

We create a matched sample between low and high overhang firms with nearest neighbor matching using the Mahalanobis distance. For each high overhang firm we match—with replacement—one low overhang firm that is its nearest neighbor in terms of average Tobin's Q, cash flow, and total assets for the period before MAP-21 (years 2009 to 2011). We match 139 unique firms in the high overhang group to 71 low overhang firms, we weight each of these low overhang firms by the number of times they were chosen as a control. In the Internet Appendix we show that differences in Tobin's Q, cash flow, and total assets are no longer statistically significant between low and high overhang firms in this matched sample.

Table 2.5 repeats the difference-in-difference analysis in this balanced sample. Findings are quantitatively similar to those of Table 2.3, the point estimate suggests that high overhang firms increased their investment rate by 2.1 percentage points after the passage of MAP-21, and the estimate is significant at the 5% significance level. This table aids in alleviating concerns that our results are biased due to sample differences between low and high overhang firms.

2.4.3 A Closer Look at the Impact of Cash Contributions

The incorporation of higher discount rates as part of MAP-21 reduces both the pension liability as well as the mandatory cash contributions, which are calculated as a function of the funding status of the plan. In Table 2.6 we investigate whether our result is driven by those firms with the highest mandatory contributions in the pre- period. We divide the sample based on median mandatory cash contributions to the pension fund prior to MAP-21. Since we cannot accurately estimate 2012 mandatory contributions had MAP-21 not been enacted, we use the average contributions from 2009-2011 as a proxy for high expected future contributions. Firms identified as having "Low Contributions" actually exhibit an economically larger change in investment in the post period. The regression

Table 2.5: **Difference-in-Differences: Matched sample**

This table presents a difference-in-differences analysis of capital expenditures scaled by lagged capital stock. $High\ Overhang$ is an indicator variable that takes the value of 1 if a firm falls above the median $Pension\ Overhang$ in the year prior to MAP-21. The sample consists of all firms with $High\ Overhang$ matched, with replacement, to firms with below median pension overhang. The match is based on the firm average of $Tobin'sQ$, cash flow, and total assets during the period before MAP-21. We control for $Tobin's\ Q$, $Cashflow$, $Overhang$, $EmployerContributions$. Tobin's Q is the market value of equity plus the book value of debt divided by the book value of assets. Tobin's Q is lagged one year. The cash flow variable is constructed following [12] to account for non-cash pension expense. Cash flow is scaled by lagged capital stock. Employer contributions are reported in plan Form 5500 filings and aggregated to the firm level.

	(1) Capex/PPE$_{t-1}$	(2) Capex/PPE$_{t-1}$
HighPenOverhang × Post	0.021**	0.022**
	(2.099)	(2.172)
Tobin's Q	0.066***	0.007
	(5.939)	(0.752)
Cashflow	0.015**	0.038***
	(2.165)	(4.615)
Overhang	−0.074	−0.020
	(−1.174)	(−0.817)
Employer Contributions	−0.025	−0.110*
	(−0.434)	(−1.858)
Firm	Yes	No
Year	Yes	No
Industry × Year	No	Yes
Observations	1,336	1,343
Within R^2	0.22	0.21
Adj. R^2	0.64	0.37

Clustering for standard errors at the firm-level for all specifications.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

results show significant point estimates in each subsample and of a magnitude similar to those shown in Table 2.3 for the full sample. A Wald test for equality of coefficients of the interaction term across the subsamples fails to reject the null hypothesis. Table 2.6 suggests the relief experienced in annual mandatory cash contributions to the firm's pension is not the primary constraint on investment.

Table 2.6: **Segmented Sample by Cash Contributions in 2011**

This table presents a difference-in-differences analysis of capital expenditures scaled by lagged capital stock. We segment the sample by the cash contribution a firm made into its pension fund in 2009-2011. Low (High) Contribution represents firms whose cash contributions are below (above) the median of all cash contribution from 2009-2011. $Post$ is an indicator variable for all years after the passage of the legislation (2012). We control for $Tobin's\ Q$, $Cash\ flow$, $Overhang$, $Employer\ Contributions$. Tobin's Q is the market value of equity plus the book value of debt divided by the book value of assets. Tobin's Q is lagged one year. The cash flow variable is constructed following [12] to account for non-cash pension expense. Cash flow is scaled by lagged capital stock. Employer contributions are reported in plan Form 5500 filings and aggregated to the firm level.

	(1) Low Contributions	(2) High Contributions
HighPenOverhang $\times$ Post	0.037***	0.014*
	(2.592)	(1.708)
Tobin's Q	0.049***	0.071***
	(5.446)	(7.017)
Cash flow	0.026**	0.010
	(2.251)	(1.099)
Overhang	-0.003	-0.170***
	(-0.035)	(-3.929)
Employer Contributions	-0.127	0.023
	(-1.005)	(0.452)
Firm	Yes	Yes
Year	Yes	Yes
Observations	938	935
Within R^2	0.18	0.27
Adj. R^2	0.68	0.64

Clustering for standard errors at the firm-level for all specifications.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The results do not point to one subsample facing higher impediments to investment than another, but rather different sensitivities to cash flow and HLW debt overhang. Cash flow has a higher impact on firms in the “Low Contribution” sample while HLW debt overhang affects “High Contribution” firms to a greater extent.

2.4.4 Impact of Pension Overhang on the Firm’s Credit Ratings

Due to the claim on future cash flows, the magnitude of firm pension obligations impact the ability to pay and the potential recovery rate of the marginal creditor. If an underfunded plan terminates, either voluntarily or involuntarily, the PBGC assumes control of the plan and can file a claim against the company’s existing assets. The degree of pension leverage would then be expected to be negatively correlated with firm credit ratings. Indeed, rating agencies are rather transparent in their treatment of pension liabilities: “Standard & Poor’s Ratings Services views unfunded liabilities relating to defined benefit pension plans and retiree medical plans as debt-like in nature... By accepting a portion of their compensation on a deferred basis, the employees essentially become creditors of the company.”[16] [29] find supportive evidence that pension sponsors with underfunded plans experience lower credit ratings.

We test these implications in an ordered probit and Table 2.7 reports results consistent with previous findings. The dependent variable is the firm’s S&P long-term credit rating reported by Compustat scaled from 1 to 20 with 1 representing a “AAA” rating and 20 a “CC” rating. The post period in these regressions excludes 2012. We want to account for a potential lag in rating changes as well as the lag in IRS Form 5500 reporting, which is not reported until approximately 7 months after the end of the plan year. Reporting could then be more than halfway into 2013 for a plan year ended in 2012.[17]

In column (1), we test whether $HighPenOverhang$ firms experience an effect on their credit rating in the post period. The negative and significant coefficient confirms these firms have a higher probability to benefit from favorable rating action after the passage of MAP-

[16] See [60]

[17] Results are qualitatively and quantitatively similar when post is defined as including 2012.

Table 2.7: **Impact on Firm Credit Ratings**

Table 2.7 reports results from an ordered probit model. The dependent variable is the Standard & Poor's long-term credit rating for the firm ordinally ranked from 1 to 20. A value of 1 is indicative of a "AAA" credit rating, while a value of 20 is equivalent to "CC". $HighPenOverhang$ is an indicator variable that takes the value of 1 if a firm falls above the median $Pension\ Overhang$ in the year prior to MAP-21. $Post$ 2013 is an indicator for years 2013-2015. $Pension\ Leverage$ is the scaled difference in the ABO less dedicated pension assets aggregated at the firm-year level. $Pension\ Leverage\ Under$ is the scaled unfunded portion of the pension liability if the firm has insufficient dedicated pension assets to cover liabilities and zero otherwise. $Pension\ Leverage\ Over$ is the scaled overfunded portion of the pension liability if pension assets exceed obligations and zero otherwise. $Debt/Assets$ includes short- and long-term debt. The market beta is calculated for each firm. $InterestCoverage$ is EBITDA divided by interest expense. $EBITDA/Sales$ is EBITDA divided by total revenue.

	(1) Credit Rating	(2) Credit Rating	(3) Credit Rating
HighPenOverhang × Post *2013*	-0.193**		
	(-2.21)		
Pension Leverage		8.462***	
		(5.62)	
Pension Leverage *Under*			8.448***
			(5.28)
Pension Leverage *Over*			-1.630
			(-0.45)
Debt/Assets	2.873***	2.800***	2.835***
	(6.21)	(6.32)	(6.36)
Beta	1.235***	1.158***	1.172***
	(5.39)	(5.67)	(5.79)
Assets	-0.697***	-0.761***	-0.756***
	(-11.37)	(-12.73)	(-12.67)
Market/Book	-0.718***	-0.817***	-0.824***
	(-8.16)	(-9.62)	(-9.85)
Interest Coverage	-0.012***	-0.011***	-0.011***
	(-5.29)	(-5.92)	(-5.81)
EBITDA/Sales	-2.511***	-2.522***	-2.427***
	(-3.15)	(-3.35)	(-3.26)
Year	Yes	Yes	Yes
Industry	Yes	Yes	Yes
Observations	1,852	2,024	2,024

Clustering for standard errors at the firm-level for all specifications.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

21. All control variables are highly significant and appear to impact ratings with the expected sign. All columns include both year and industry fixed effects to control for changes in rating standards over time ([58]). Column (2) suggests pension leverage, defined as the unfunded portion of the aggregate U.S. pension liability scaled by assets, is associated with lower credit ratings. [29] highlights the differential impact for underfunded versus overfunded liabilities. If a firm with an overfunded aggregate pension liability attempts to revert the surplus it faces steep tax consequences such the impact on ratings is likely not symmetrical. Column (3) differentiates between firms with underfunded versus overfunded plans. $Pension\ Leverage\ Under$ is the scaled unfunded portion of the pension liability if the firm has insufficient dedicated pension assets to cover liabilities and zero otherwise. We define $Pension\ Leverage\ Over$ in a similar manner for firms with overfunded pension liabilities. The positive and highly significant coefficient on $Pension\ Leverage\ Under$ indicates the result in column (2) is driven by underfunded plans. Consistent with prior findings, we observe that overfunding the pension liability does not appear to have a beneficial impact on firm ratings.

We follow [61] in interpreting the economic magnitude of the effects for the ordered probit. Evaluating the model at the mean values for all variables suggests the average hypothetical firm would be rated "BBB+". This compares to an average rating of between "BBB" and "BBB-" in our sample. Based on the magnitude of the coefficient on the interaction term in column (1), $HighPenOverhang$ firms experience a one-third notch better rating in the post period. For reference, based on the estimate in column (2), a one standard deviation change in $Pension\ Leverage$ and $Debt/Assets$ equates to a one-quarter and one-half notch change, respectively.

2.4.5 Pension Overhang and Measures of Financial Constraints

Firms facing higher costs in accessing external capital markets may experience an outsized benefit from the passage of MAP-21. We investigate if firms facing tighter financing constraints (incremental to pension overhang effects) increased investment more after the passage of MAP-21. We utilize measures of financial constraints which may capture an incremental impact to the negative effect pension overhang has on firm investment.

We employ the financing constraints index of [44], also called the Size-Age index since it is a function of the log of book assets, its squared value, and the age of the company. [44] argue this index is a particularly useful predictor of financial constraints relative to prior proxies such as the Kaplan-Zingales index.[18] These authors also show that firms with high cash holdings experience greater financial constraints consistent with a theory of precautionary holdings, thus we also segment our sample by the ratio of cash holdings to book assets.

We complement the Size-Age index with the financing constraints index of [45], this index is based on textual analysis of firms' 10-K reports, in particular the Capitalization and Liquidity subsection. [45] construct different scores for financing constraints, we use their overall measure for delay investment score. In addition, we explore the interaction with small firms as defined by their book assets. We abstain from separating the sample by credit ratings as these are factored into our measure of pension overhang.

We create an indicator that equals 1 if a firm is above (below for size) the median value variable in the year prior to MAP-21 passage and then interact this indicator with our $HighPenOverhang$ and $Post$ indicators. We present the results from these triple interactions in Table 2.8.[19] Results are consistent with our hypothesis that MAP-21 created greater relief for incrementally financially constrained firms. High overhang companies with more restrictive financial constraints—as measured by the Size-Age index prior to passage of the law—increased their investment 3.2 percentage points after MAP-21. Results for the Hoberg-Maksimovic textual analysis index are very similar in magnitude, yet shy of statistical significance potentially due to the decrease in sample size. The Hoberg-Maksimovic

[18] We also refrain from using the Kaplan-Zingales or Whited-Wu index since their computation include measures of leverage which create a mechanical correlation with debt overhang.

[19] Results including all interaction terms are included in the Appendix

Table 2.8: **Financial Constraints and Pension Overhang**

Table 2.8 displays regression results including interaction terms for various measures of firm financial constraints. *High* designates a firm falling above the median for each financial constraint proxy in the year prior to MAP-21. The $Size - Age$ Index is defined in accordance with [44]. $Hoberg - Maksimovik$ represents the financing constraints index based on textual analysis of [45]. $Cash$ references cash and cash equivalents scaled by total assets. $Small$ references firm size based on total assets. $Post$ is an indicator variable for all years after the passage of the legislation (2012). We control for $Tobin's\ Q$, $Cash\ flow$, $Overhang$, $Employer\ Contributions$. Tobin's Q is the market value of equity plus the book value of debt divided by the book value of assets. Tobin's Q is lagged one year. The cash flow variable is constructed following [12] to account for non-cash pension expense. Cash flow is scaled by lagged capital stock. Employer contributions are reported in plan Form 5500 filings and aggregated to the firm level.

	(1) Capex/PPE$_{t-1}$	(2) Capex/PPE$_{t-1}$	(3) Capex/PPE$_{t-1}$	(4) Capex/PPE$_{t-1}$
HighPenOverhang × Post × High Size-Age	0.032**			
	(2.023)			
HighPenOverhang × Post × High Hoberg-Maksimovic		0.029		
		(1.573)		
HighPenOverhang × Post × High Cash			0.042***	
			(3.115)	
HighPenOverhang × Post × Small				0.028
				(1.344)
Tobin's Q	0.058***	0.059***	0.058***	0.058***
	(8.093)	(6.510)	(8.162)	(7.912)
Cash flow	0.019***	0.021**	0.018**	0.018***
	(2.721)	(2.238)	(2.502)	(2.617)
Overhang	−0.075	−0.067	−0.069	−0.083
	(−1.278)	(−1.009)	(−1.167)	(−1.481)
Employer Contributions	−0.031	−0.044	−0.037	−0.032
	(−0.510)	(−0.574)	(−0.640)	(−0.565)
Firm	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Observations	1,854	1,368	1,873	1,873
Within R^2	0.21	0.23	0.22	0.21
Adj. R^2	0.66	0.66	0.66	0.66

Clustering for standard errors at the firm-level for all specifications.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

measure does not include firms without a machine readable subsection on capitalization and liquidity in the 10-K. Firms with high cash holdings and high pension overhang increased investment by approximately 4.2 percentage points in the post period. The coefficient on the triple interaction with small firms is not significant, yet the direction and magnitude of the point estimate is consistent with these firms experiencing a higher degree of financial constraint prior to MAP-21.

2.4.6 Pension Overhang and CEO Incentives

In this section we investigate if firms whose CEO had greater incentives in their compensation structure — such as stock options — increased investment more aggressively after MAP-21. Prior literature has shown that CEOs with higher pay-for-performance sensitivity tend to invest more sharply ([46]), while [62] suggest managerial incentives impact pension funding and allocations, particularly as distance to default narrows. We extend the analysis to examine the cross-section of CEO compensation horizon and pension overhang. Managers with short-term horizons are susceptible to myopic behavior consistent with foregone investment ([63]).

We obtain CEO compensation information from Execucomp and follow [46] in computing two variables of pay-for-performance sensitivity: delta and vega. We follow [64] in calculating manager compensation horizon. Delta measures the percent change in value of the CEO's portfolio of outstanding stocks and options awarded to a one percent change in the company's stock price; vega measures the sensitivity of the CEO's portfolio to increased volatility in the company's stock price. The effect of delta on the decision-making process is ex ante ambiguous. The manager is closely aligned with shareholders in either context, yet may manage downside risk given a high concentration to firm-specific outcomes ([46]; [65]). However, in the case of vega, option compensation clearly incentivizes a greater degree of risk-taking behavior.

We present our results in Table 2.9. We test if CEOs of firms with high pension over-

Table 2.9: **CEO Compensation**

This table displays regression results including interaction terms for various measures of incentives in CEO compensation. *High Delta* (*High Vega*) designates a firm with above median Delta (Vega) in CEO compensation in the year prior to MAP-21. High Horizon is an indicator for a firm with above median CEO compensation horizon. $Post$ is an indicator variable for all years after the passage of the legislation (2012). We control for $Tobin's\ Q$, $Cash\ flow$, $Overhang$, $Employer\ Contributions$. Tobin's Q is the market value of equity plus the book value of debt divided by the book value of assets. Tobin's Q is lagged one year. The cash flow variable is constructed following [12] to account for non-cash pension expense. Cash flow is scaled by lagged capital stock. Employer contributions are reported in plan Form 5500 filings and aggregated to the firm level.

	(1) Capex/PPE$_{t-1}$	(2) Capex/PPE$_{t-1}$	(3) Capex/PPE$_{t-1}$
HighPenOverhang × Post × High Delta	0.027* (1.788)		
HighPenOverhang × Post × High Vega		0.038** (2.387)	
HighPenOverhang × Post × High Horizon			0.031** (1.991)
Tobin's Q	0.051*** (7.973)	0.050*** (7.856)	0.052*** (6.221)
Cashflow	0.021*** (2.598)	0.020** (2.538)	0.021** (2.418)
Overhang	−0.058 (−0.714)	−0.055 (−0.700)	−0.146** (−2.491)
Employer Contributions	−0.032 (−0.473)	−0.031 (−0.467)	0.003 (0.056)
Firm	Yes	Yes	Yes
Year	Yes	Yes	Yes
Observations	1,513	1,513	1,252
Within R^2	0.19	0.19	0.20
Adj. R^2	0.68	0.68	0.67

Clustering for standard errors at the firm-level for all specifications.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

hang and higher pay-for-perfomance measures or a longer compensation horizon in the year prior to MAP-21 increased their investment more aggressively after the passage of the law. Results are consistent with our hypothesis that CEOs with more pay-for-performance sensitivity increased their investment rate to a greater extent after passage of the law.[20] For those firms with a CEO falling above the median measure of delta and vega in 2011, the firm increased investment 2.7 - 3.8% more after the passage of MAP-21. Notably, the effect of vega suggests a greater statistical and economic impact as anticipated. We examine the effect of manager horizon in column (3). CEOs with compensation associated with a longer vesting schedule invest considerably more after the passage of the law. The prior results are consistent with and complement the results of [62]. The authors find CFO rather than CEO compensation sensitivity is closely related with pension funding levels and asset allocation, while investment policy is likely determined by the CEO. In untabulated results, we find evaluating these measures using CFO compensation does not yield statistically significant results.

2.5 Robustness

2.5.1 Frozen Plans

The pension overhang measure we construct assumes a uniform maturity of the pension deficit over time and across firms that is consistent with the long-term nature of pension liabilities. If the pension plan remains open to new participants, we see the methodology as a fair representation of the weighted average maturity of the pension obligations, which should remain relatively stable as employees retire and younger employees are hired. Over the past decade, there has been a shift toward freezing defined benefit plans. When a DB plan is frozen it is generally closed to new entrants and in many instances current employees no longer accrue benefits based on the DB structure. Rather, existing employees are often transitioned into a defined contribution plan which does not create a long-term liability

[20] Results including all interaction terms are included in the Appendix

for the firm. Under these circumstances, a frozen defined benefit pension plan would be expected to have shorter duration pension liabilities.[21]

Table 2.10: **Frozen Pension Plans**

This table presents a difference-in-differences analysis of capital expenditures scaled by lagged capital stock. We segment the sample by firms where their largest plan, by liabilities, is frozen by 2011 and those where it is not. Column 3 adds a control variable for the percentage of $Active\ Plan\ Participants$ relative to total participants. $Post$ is an indicator variable for all years after the passage of the legislation (2012). We control for $Tobin's\ Q$, $Cash\ flow$, $Overhang$, $Employer\ Contributions$. Tobin's Q is the market value of equity plus the book value of debt divided by the book value of assets. Tobin's Q is lagged one year. The cash flow variable is constructed following [12] to account for non-cash pension expense. Cash flow is scaled by lagged capital stock. Employer contributions are reported in plan Form 5500 filings and aggregated to the firm level.

	(1) Frozen Plans	(2) Non-Frozen Plans	(3) Full Sample
High Overhang × Post	0.033**	0.020***	0.023***
	(2.085)	(2.706)	(3.347)
Tobin's Q	0.058***	0.058***	0.058***
	(4.015)	(7.165)	(8.150)
Cashflow	0.017	0.019**	0.018**
	(1.451)	(2.211)	(2.562)
Overhang	−0.186***	−0.024	−0.088
	(−2.808)	(−0.312)	(−1.520)
Employer Contributions	−0.062*	−0.037	−0.036
	(−1.673)	(−0.459)	(−0.680)
Active Plan Participants			−0.004
			(−0.157)
Firm	Yes	Yes	Yes
Year	Yes	Yes	Yes
Observations	456	1,417	1,870
Within R^2	0.21	0.22	0.20
Adj. R^2	0.70	0.64	0.66

Clustering for standard errors at the firm-level for all specifications.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

We test the implications in Table 2.10 by dividing the sample into firms where their largest pension plan, in term of liabilities, is frozen by 2011 and those where it is not.

[21] We thank Irina Stefanescu and Chris Yung for this suggestion.

Approximately one-quarter of the plans in our sample are frozen by the year prior to the passage of MAP-21. The actual duration of plan liabilities is not available, yet the Form 5500 data does delineate if a plan is frozen. The coefficients in both columns (1) and (2) are statistically significant and similar to the point estimates in Table 2.3. Any differences in the duration of plan liabilities between firms with frozen and open plans do not seem to drive the main result. In column (3) we alternatively control for the percentage of 'active participants', the percentage of plan beneficiaries currently employed. We do not find any effect on firm investment.

2.5.2 Marginal Tax Rates as Alternative Explanation

The changes to pension discount rates as part of MAP-21 were intended to raise additional revenue for the government by lowering tax-deductible pension contributions. Thus, high marginal tax firms prior to the law change may seek other forms of tax shelters such as increasing investment for purposes of the depreciation expense deduction. In Table 2.11, we explore this alternative hypothesis which may impact investment policy. We test whether an increase in investment is driven by firms with ex-ante high marginal tax rates. Ex ante, firms with the highest marginal tax rates would experience the greatest benefit from the the pension contribution tax shield. These firms may have a material incentive to shelter earnings through different means after the law change. [50] document the material tax benefits gained from pension contributions, notably from firms sponsoring larger plans. Despite the decrease in mandatory contributions, firms may still receive favorable tax treatment on pension contributions up to certain limits of their funded status. The ability to contribute beyond the minimums however, would be expected to reduce the incentives to seek alternative tax shelters.

We merge marginal tax rates from John Graham's website with our dataset.[22] We use an indicator variable, denoted as "High Tax" for firms with above median marginal tax rates

[22]https://faculty.fuqua.duke.edu/ jgraham/taxform.html

Table 2.11: **Effect of Marginal Tax Rates**

In this table we explore an alternative channel, tax shields from depreciation expense. $High\,Tax$ is an indicator variable that takes the value of 1 if a firm falls above the median marginal tax rate in the year prior to MAP-21. $Post$ is an indicator variable for all years after the passage of the legislation (2012). We control for $Tobin's\ Q$, $Cash\ flow$, $Overhang$, $Employer\ Contributions$. Tobin's Q is the market value of equity plus the book value of debt divided by the book value of assets. Tobin's Q is lagged one year. The cash flow variable is constructed following [12] to account for non-cash pension expense. Cash flow is scaled by lagged capital stock. Employer contributions are reported in plan Form 5500 filings and aggregated to the firm level.

	(1) Capex/PPE$_{t-1}$	(2) Capex/PPE$_{t-1}$	(3) Capex/PPE$_{t-1}$
High Tax Rate × Post	-0.006	-0.007	-0.007
	(-0.816)	(-0.816)	(-0.823)
Tobin's Q	0.049^{***}	0.058^{***}	0.058^{***}
	(6.942)	(7.897)	(7.897)
Cash flow	0.026^{***}	0.019^{***}	0.019^{***}
	(3.761)	(2.830)	(2.810)
Overhang		-0.086	-0.091
		(-1.214)	(-1.337)
Employer Contributions			-0.046
			(-0.796)
Firm	Yes	Yes	No
Year	Yes	Yes	Yes
Observations	2,922	1,808	1,808
Within R^2	0.15	0.21	0.21
Adj. R^2	0.60	0.68	0.68

Clustering for standard errors at the firm-level for all specifications.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

prior to the implementation of MAP-21. We find no significant results for the models using investment as a dependent variable. Although alternative tax shelters are worth exploring, the results suggest that tax implications do not explain the previous findings.

2.6 Conclusion

In this paper, we develop a measure of pension overhang incorporating the shortfall in unfunded pension liabilities. We find an incremental impact of the pension overhang on capital expenditure spending, while controlling for the measures correlated with the investment opportunity set and those shown to drive investment policy. We use an exogenous shock to discount rates induced by MAP-21 to show the causal impact of pension overhang on firm investment in contrast to the mixed results in the literature that focuses on the cash flow effects of pensions and their impact on investment. The small economic magnitude of annual mandatory contributions and firm's ability to voluntarily contribute above the required funding amount make it challenging to evaluate the cash flow effects of pension shortfalls. We shed light on the relationship between corporate investment policy and unfunded pension liabilities through an alternative lens—pension debt overhang.

We do not take a stance on the optimal, market-driven value of the pension liability, but rather examine firm policy in response to a shock to the valuation of outstanding liabilities. The results indicate that single-employer pension plan sponsors do not manage corporate policy toward either an optimal or market-implied discount rate. Rather, the rates mandated by legislation impact policy decisions through their effect on firm leverage.

CHAPTER 3

DEFAULT RISK AND THE PRICING OF U.S. SOVEREIGN BONDS

3.1 Introduction

Does United States Treasury default risk have the same impact on the pricing of all U.S. Treasury obligations? We investigate this question through the lens of the relative pricing of nominal and inflation protected Treasury securities. Our interest is motivated by the pair-wise mispricing between nominal and real bonds documented in [66]. The authors show that a strategy replicating inflation-protected securities through inflation swaps, STRIPs, and nominal Treasuries generates large and persistent arbitrage profits. Their empirical analysis suggests that much of the profitability of the strategy is likely to be explained by slow-moving capital that prevented the profits from being arbitraged away. Our study asks if part of this differential might be accounted for by differences in exposures to default risk present in nominal and inflation-protected (TIPS) Treasury securities.

Our investigation of the role of default risk in this pricing differential may be surprising given the frequent treatment of Treasury obligations as default risk-free. However, the financial crisis of 2008-2009 and its aftermath have suggested that this perception may need to change. [67] note that the premium paid to insure U.S. sovereign debt as measured by credit default swap (CDS) spreads rose to nearly 100 basis points during the crisis, and remained elevated since. The authors show that a macro-finance model with a non-trivial probability of sovereign default can replicate this pattern in the United States and other developed markets. Repeated political conflict over the debt ceiling in the United States in 2011, 2013, and 2017 has also contributed to questions about the risk-free status of U.S. sovereign debt. The 2011 conflict led to Standard and Poor's downgrading the status of the United States Treasury as an obligor from AAA to AA+.

Even if a default is possible, why might we see a resulting differential in the pricing of nominal and inflation-protected debt? History suggests that there is considerable uncertainty as to how forms of debt might be treated in the case of a sovereign default. As discussed in [68], sovereign defaults rarely play out in the way modeled in structural or reduced form models of corporate credit risk. Rather than a single event, a sovereign entity weighs the costs and benefits of continuing to pay its obligations against the reputational cost of default. When default occurs, it is more likely that the debt will be restructured or renegotiated than that an outright liquidation will take place. This renegotiation involves a considerable amount of uncertainty. [68] examine the case of the Russian default on its ruble-denominated debt in 1998, and its impact on dollar-denominated MinFins. The authors show that uncertainty around the treatment of this debt, which was considered domestic, relative to foreign Eurobonds had a large impact on the relative pricing of the obligations. Similarly, [69] examine the variation in ultimate recovery in present value terms of holders of Greek debt during the 2012 restructuring. All bondholders were provided the same package of securities, which implied large differences in present value loss given default across holders of different bonds.[1]

With this background in mind, our empirical work examines the question of whether the spread between like-maturity inflation swaps (ILS) and breakeven inflation (BEI), the difference between yields of nominal and inflation-protected U.S. Treasuries, is correlated with default risk. Using spreads on CDS written on U.S. Treasury obligations to proxy for overall risk of default, we find a statistically and economically significant relation between the ILS-BEI spread and CDS spreads. Specifically, over the period 2008 through 2015, a one standard deviation increase in the CDS spread (16 basis points) is associated with a 3.1 basis point increase in the hedged breakeven inflation, about 10% of the average ILS-BEI spread throughout our sample.[2] This relation is not simply a manifestation of dislocation

[1] In Figure 5 of [69] titled "Bond-by-bond haircuts, by remaining duration," the authors show significant heterogeneity across maturities in haircuts suffered by holders of nominal Greek debt, ranging from 20% to 90%.

[2] Hedged breakeven inflation is defined as the spread between the inflation-linked swap rate and the

during the financial crisis; the result holds in the subsample from 2010 onward. In fact, the statistical significance of coefficient estimates on CDS spreads increases in the post-crisis sample. Furthermore, we demonstrate that the relation is robust to controls for liquidity and slow-moving capital. Lastly, we extend our empirical tests using the U.K. data to verify our hypothesis. Consistent with our U.S. results, the U.K. ILS-BEI spread loads positively and significantly on U.K. CDS spreads after the crisis.

In order to better understand the source of this covariation, we derive a new affine model of defaultable nominal and inflation-protected sovereign debt building on [70]. In this model, a sovereign entity issues multiple bonds with differences in their possible losses given default. We view this modeling approach as a convenient way to capture uncertainty surrounding the treatment of different bonds in case of default, such as the renegotiation of Russian and Greek bonds discussed above. In our context, this uncertainty applies to the treatment of U.S. sovereign bonds in case of a default. The specific uncertainty that we have in mind relates to whether a default event would trigger a default on all U.S. Treasury obligations and, if so, the ultimate recovery of present value of the bonds under consideration.[3] For example, concerns about whether the inflation indexing of TIPS would be removed upon default would generate uncertainty about whether TIPS investors would effectively suffer deeper losses of present value than nominal Treasury bond holders. The closed-form pricing formulae in our model explicitly relate the spread between inflation-linked swaps and the breakeven inflation rate implied by the prices of nominal and inflation-indexed securities to differences in loss given default.

We estimate the parameters of the model with the extended Kalman filter, targeting the term structures of overnight indexed swaps (OIS), inflation-linked swaps, nominal Treasuries, TIPS, and CDS. For each of these five term structures, we fit five maturities between one and ten years. Additionally, our estimation includes the inflation and a proxy for TIPS

Treasury-based breakeven inflation rate of the same maturity (ILS-BEI).

[3]The law is not clear on whether cross-default provisions apply to U.S. Treasury debt. According to [71], “It is unclear whether any U.S. debt securities contain cross-default clauses. The statute setting forth procedures for the U.S. government to issue debt securities makes no mention of these types of clauses ...”

liquidity, for a total of 27 time series. The model is characterized by six factors: three nominal and real term structure factors, two credit factors, and one liquidity factor. Our results indicate that the model is able to simultaneously capture most of the variation in all observable variables, showing outstanding fitting performance for a relatively low number of factors, with most R^2 measures exceeding 90%. A decomposition of the spreads between ILS and Treasury breakevens and show that credit risk factors are able to capture between approximately 50% and 100% of the total ILS-BEI variation during our sample period. The remaining variation is explained by illiquidity issues in the TIPS market, specifically at the height of the crisis in 2008-2009. The results support our conjecture that nominal and inflation-protected treasuries are affected differently by sovereign default risk.

Our paper contributes to at least three broad strands of the fixed income literature. The first area to which we contribute is the relative pricing of nominal and inflation-protected securities. This literature seeks to extract information about inflation risk premia, inflation or deflation expectations, and mispricing from Treasury prices.[4] Most closely related to our analysis, [66] document apparent no-arbitrage violations in the pricing of nominal and inflation-protected securities, and conclude that the arbitrage arises due to slow-moving capital. Their arbitrage measure is closely related to the hedged ILS-BEI spread used in our empirical analysis. We differ from this and other papers in the literature in explicitly considering the impact of default risk on the relative pricing of nominal and inflation-protected securities. Our results suggest that part of the pricing differential is related to credit risk.[5]

A second strand of literature investigates the role that liquidity risk plays in driving the difference in TIPS and nominal Treasury prices.[6]. [86] suggest that there is a large and

[4][72], [73], [74], [75], [76], and [77] examine reduced-form affine pricing models for the purpose of extracting information about inflation risk premia. [78] and [79] extract deflation probabilities from real Treasuries.

[5][66] note that inflation-protected securities are not necessarily default risk-free, but suggest that since CDS do not distinguish between nominal and inflation-protected debt, default risk is unlikely to explain the arbitrage profits. See also [80] for a related analysis in the Euro-Area context.

[6][81] construct inflation risk premia employing only TIPS yields and control for the liquidity premium between TIPS and nominal bonds. [82] decompose real and nominal yields into liquidity, inflation, and real

economically significant liquidity premium that affects the relative pricing of nominal and real bonds in both the U.S. and the U.K, and that this liquidity premium is largely captured by the ILS-BEI that is the focus of our empirical work. [87] and [88] also use the ILS-BEI spread as a proxy for liquidity risk because high liquidity is attributed to the swap market in the U.S. Our analysis suggests that the ILS-BEI differential reflects not just a liquidity risk premium, but also a credit risk premium.

The third strand of literature investigates the role of default risk in the pricing of sovereign securities and CDS. [67] use the rise in CDS premia in the U.S. and developed countries after the crisis to motivate a macrofinance model in which CDS premia reflect default probabilities.[7] Their model is able to generate the high premium paid to insure U.S. sovereign debt. The authors' framework contrasts with friction-based explanations for CDS premia such as counterparty risk as in [91] or financial regulation as in [92].[8]. Our paper similarly considers U.S. default with non-trivial probability but focuses on the effect of default risk on the relative pricing of different securities issued by a sovereign entity.

3.2 The Case of a U.S. Default

Our empirical analysis crucially relies on four notable financial instruments, namely credit default swaps on the U.S. government (CDS), sovereign U.S. nominal and inflation-indexed bonds, and inflation-indexed swaps. This Section details the important institutional features of these market instruments.

interest rate risk components in an affine term structure model and conclude that forward breakeven inflation is primarily driven by risk and liquidity premia. [83] propose a substantial liquidity premium as the primary factor driving the wedge between TIPS yields and real risk-free rates, thus causing distortions in the term structure of breakeven inflation. [84] identify liquidity risk in TIPS with the average deviation across bonds from the predictions of a no-arbitrage pricing model. Finally, [85] can be interpreted to suggest that the ILS-BEI could be related to intermediary balance sheet constraints.

[7]Related work by [89] estimates an affine multi-factor model of U.S. and European state and country credit default swaps and concludes that systemic sovereign risk is strongly linked to financial market variables. [90] provide an extended analysis for a cross-section of 38 different countries.

[8][93] show that counterparty risk is priced in the CDS market using data covering the height of the 2008 crisis, but the magnitude is trivial because of the full collateralization of CDS liabilities. A summary of potential drivers of CDS spreads is also provided in survey of [94] and the references therein.

3.2.1 Nominal Treasuries and TIPS

The main two instruments of debt issuance for the U.S. government are cash-denominated Treasuries (nominal) and *Treasury inflation-protected securities* (TIPS). Nominal zero-coupon bonds pay their nominal face value to the bond-holder at maturity. In contrast, zero-coupon TIPS holders earn the inflation-adjusted face value of the bond at maturity. Since cumulative inflation tends to be positive, TIPS tend to trade at a premium compared to nominal bonds. For both nominal bonds and TIPS, yields at issuance are determined through an auction process involving numerous market participants. According to Treasury Direct, as of April, 2020, the total principal value of Treasury securities outstanding is $18,104 billion, of which $1,493 billion, or 8% are TIPS. The dollar amount of TIPS outstanding is comparable in magnitude to each of the respective markets for asset-backed securities, federal agency securities, and U.S. money market instruments.[9]

The TIPS inflation adjustment is computed using the *seasonally non-adjusted consumer price index* for all urban consumers in the U.S. (CPI-U). CPI data is published monthly by the Bureau of Labor Statistics with a lag of about one and a half months, making the realized inflation unavailable when TIPS mature. TIPS payments thus include an *indexation lag* — the index used to determine their cashflows is a linear interpolation of CPI-U observed between two and three months before. The inflation-adjusted principal paid back at maturity is calculated by multiplying the face value of the bond by the cumulative *index ratio*. TIPS embed a *deflation floor*, such that they return the full face value even if cumulative inflation realized over the bond lifetime is negative.[10]

Despite the indexation lag, it would be difficult for the U.S. government to inflate away outstanding TIPS. Technically, it would be possible for the sovereign to resort to seigno-

[9] https://www.sifma.org/resources/research/fixed-income-chart/

[10] We consider zero coupon bonds in this study. Note however that most of nominal bonds and TIPS issued by the U.S. sovereign are coupon bonds paying on a semi-annual basis, but TIPS are only issued in terms of five, ten, twenty, or thirty years. For TIPS coupon payments, the coupon rate is fixed and paid on the inflation adjusted principal. For coupon payments, there is no deflation floor and the inflation-adjustment is computed using the index ratio realized over the last 6 months.

riage to pay back maturing TIPS and current coupon payments without realizing the consequence of increased inflation. However, the inflation adjustment will materially impact any remaining outstanding TIPS, increasing the future interest payments of the government. Should the U.S. government refuse to honor the TIPS indexation, this would likely trigger a credit event and force the payoff of U.S. CDS contracts (see below). In case of default, nominal bonds and TIPS have the same level of seniority.

Leaving aside the embedded deflation floor, TIPS can be theoretically replicated by combining nominal bonds and inflation-linked swaps (ILS), as shown in [66]. ILS allow for the buyer to earn cumulative inflation in exchange for a fixed rate, relative to the notional agreed upon at inception. Inflation swaps are costless to write, and they are typically zero-coupon. As of April 2012, the average daily brokered inflation swap activity was estimated to be $350 million, concentrated around the 10-year maturity. Importantly, despite a low trading frequency averaging about 2.2 contracts per day, the market for inflation swaps appears fairly liquid, with bid-ask spreads from proprietary data averaging below 3 basis points.[11] Keeping with the standard for swap contracts, ILS are collateralized, thus subject to minimal counterparty risk. In the remainder of the paper, we will assume that ILS are virtually risk-free.

In a frictionless economy, for a given maturity n, no arbitrage implies that the zero-coupon ILS rate is equal to the spread between the nominal and TIPS zero-coupon yields, called *breakeven inflation rate* (BEI):

$$\mathrm{ILS}_t^{(n)} = R_t^{(n)} - R_t^{*(n)} = \mathrm{BEI}_t^{(n)}\,. \tag{3.1}$$

This measure is the zero-coupon equivalent of [66], who show that the cash flows of any traded nominal Treasury bond can be replicated by a portfolio of TIPS, U.S. Treasury STRIPS, and inflation swaps. We equivalently call this spread ILS-BEI, *mispricing*, or

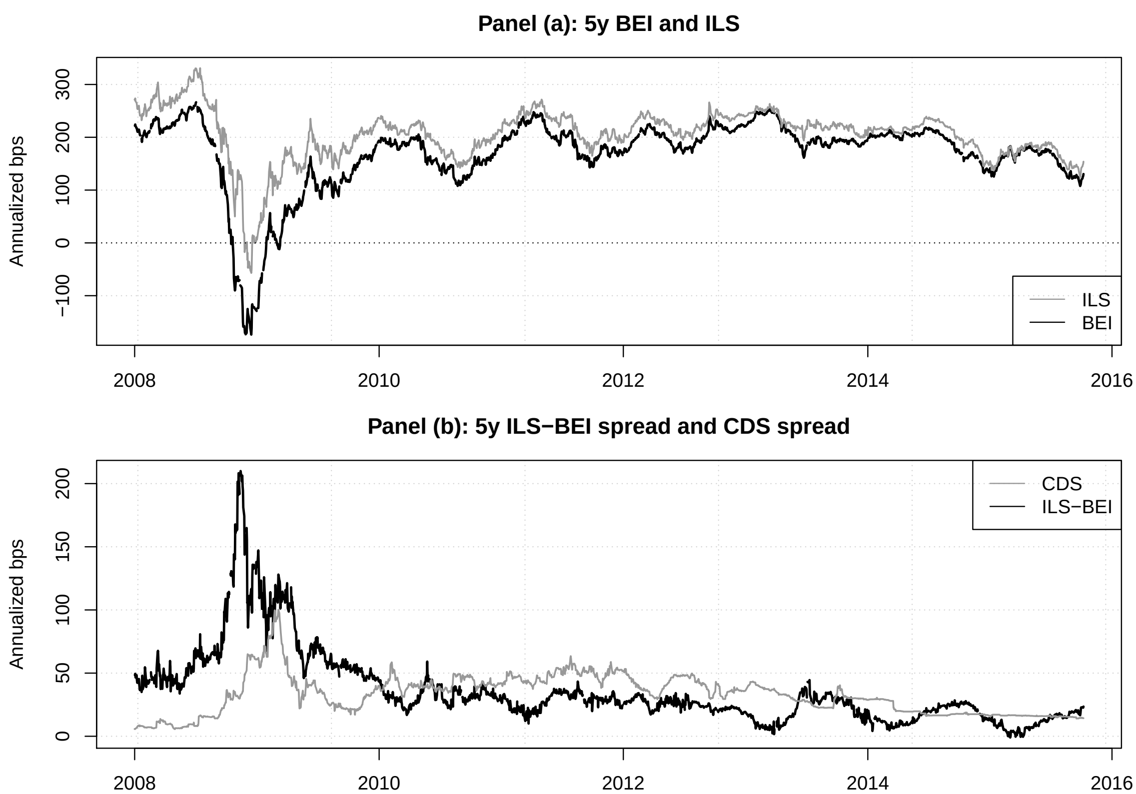
[11] https://libertystreeteconomics.newyorkfed.org/2013/04/how-liquid-is-the-inflation-swap-market.html and *JPMorgan Investment Insight: Inflation Derivatives.*

hedged breakeven.

In practice, researchers have observed large deviations from this no-arbitrage relationship over the maturity spectrum. Figure 3.1 and Figure 3.2 present the five years to maturity series of ILS and BEI and the term structure of the spread between inflation swap rates and zero-coupon BEI, respectively. These deviations from the no-arbitrage relationship are quite persistent, and average between 30 and 36 basis points depending on the maturity. In the midst of the crisis, they reached more than 200 basis points.

Figure 3.1: Five-year inflation-linked swap and breakeven inflation rate

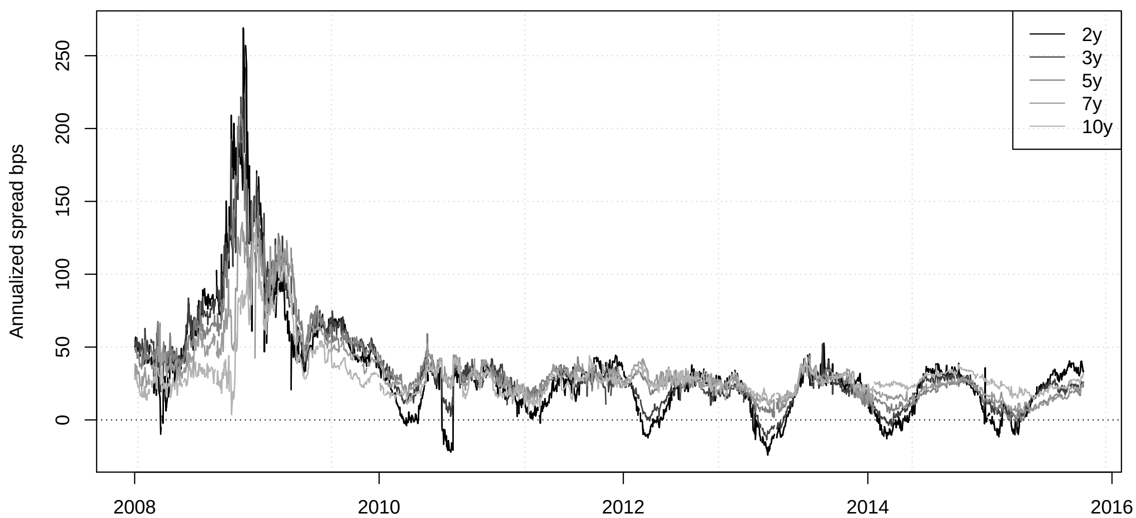
This figure presents the ILS and BEI daily zero-coupon data for the 5-year maturity from 2005 to 2016 on panel (a). ILS data is taken from bloomberg while nominal and TIPS zero coupon yields are taken from GSW 2006 and 2010 database. Panel (b) presents the spread between ILS-BEI and the CDS spread on the same graph.



Most of this apparent mispricing has been previously attributed to the low liquidity of TIPS relative to nominal bonds and ILS or to slow-moving capital (see e.g. [83] or [66]). [95] suggest the premium is related to the cost of supplying inflation protection and is

Figure 3.2: Spread between zero-coupon inflation-linked swaps and breakevens

This plot presents daily data of the spread between zero-coupon inflation-linked swaps and breakevens of the corresponding maturity, from January 2008 to October 2015. ILS data is taken from Bloomberg while nominal and TIPS zero-coupon yields are taken from GSW 2006 and 2010 database. Maturities range from 2 years (black line) to 10 years (light grey line).



typical under normal market conditions. Inflation swaps, Treasuries, and TIPS all trade over-the-counter and may be subject to varying liquidity risk or counterparty credit risk in the case of ILS. We argue that the ILS-BEI spread is also significantly related to the risk of default of the U.S. sovereign that we associate with U.S. CDS. In our analysis, we control for all these potential confounding factors in the analysis, and abstract away from the embedded deflation floor in TIPS and the tax-related issues. We note that the deflation floor drives the price of TIPS upward, making the observed TIPS yield lower than the one used in the no-arbitrage argument. This would lead us to *underestimate* the ILS-BEI spread, thus the size of the potential mispricing.

3.2.2 U.S. Sovereign CDS

Credit default swaps (CDS) are OTC instruments designed to protect bond investors from a contingent *credit event* of the issuing entity. In practice, a bond investor (*protection* *buyer*) entering a CDS agrees to pay a fixed premium, typically called the *CDS spread*, on a regular basis to the *protection seller*, her counterparty. In case of a credit event, the contract terminates and the seller has to deliver the *loss given default* (LGD) realized on the bond to the buyer, making her earn the entire face value of the bond upon default. As is standard for swap contracts, the premium is indexed on a notional amount agreed upon at inception and is set such that the original cost of issuance is zero. While not free from counterparty credit risk, CDS are typically collateralized.

The International Swaps and Derivatives Association (ISDA) provides legal details that define the triggers for the termination of CDS, which type of obligations are considered, and how the LGD and repayment operates depending on the underlying bond issuer (see [96, 97]). In the case of the United States Treasury, a credit event is observed whenever the government either *(i)* fails to repay, *(ii)* repudiates or imposes a moratorium, or *(iii)* restructures any of its borrowed money. This includes in particular any Treasury Bill, Bond or Note, whether nominal or indexed. In our empirical analysis, we identify default with the conditions for which CDS protection are triggered.

In the case of a credit event, the LGD is determined through an auction addressed to CDS dealer banks. Participating banks typically submit a bid and ask quote on a $100 face-value bond of the reference entity, and the cross-section of bid-asks is used to determine the final price of the bond, typically below par (see [98]).[12]

Settlement of the CDS contract can be completed either through cash or physical delivery. In the former case, the protection seller delivers a payment equal to the LGD as determined by the auction, multiplied by the notional of the CDS. In the latter case, the protection seller pays the entire notional to the buyer in exchange for an equivalent principal amount of reference bonds. If these bonds have the exact same characteristics as those auctioned, the two deliveries would be equivalent. However, the protection buyer can choose to exchange *any of her reference bonds* with maturity below 30 years and above the

[12]The final price of the bond resulting from this auction is published by CreditEx (http://www.creditfixings.com/CreditEventAuctions/results.jsp).

maturity of the CDS contract. This essentially embeds a *cheapest-to-deliver* (CtD) option to the buyer's position, who will likely deliver the lowest dollar price reference obligation available.[13]

U.S. CDS contracts fall under the "Big Bang Protocol" established by ISDA in 2009. In the aftermath of the financial crisis, as the primary industry body overseeing swaps and derivative trading, ISDA pushed swap market participants to adopt the new protocol in an effort to standardize over-the-counter contract parameters.[14] A number of the implemented changes are worth highlighting. First, coupon payments on each contract are fixed at either 100 (investment grade) or 500 basis points (non-investment grade). As a result, there is typically a payment to be made at the initiation of the contract to ensure that the present values of expected cash flows are equal between the buyer's and seller's legs. A second important change stemming from the protocol is the hardwiring of the auction process following credit events such that all protection buyers obtain fair cash payments from protection sellers. Third, the protocol further stipulates the creation of Determinations Committees for determining whether a credit or succession event has occurred in order to reduce disputes between counterparties in case there is ambiguity.

Market participants in the sovereign CDS market include security dealers, banks and other financial institutions, and hedge funds (see e.g. [94]). There is evidence that sovereign CDS contracts are used in both a hedging and speculative context. For contracts specifically written on the U.S. sovereign, focusing on the most liquid contracts with five years to maturity, price data from Markit shows there is very little pricing movement before the financial crisis of 2008. The premium spiked in 2009, at the height of the crisis, to about 100 basis points and has remained elevated afterward between 20 to 40 basis points.

[13] In the context of the Greek crisis, CDS contracts and the associated auction mechanism played a minor role in the resturcturing process. As highlighted by [69], the credit event was triggered only after the preemptive debt restucturing. Therefore, the CDS auction took place after the bond exchange, and the resulting auction price fell in place with the new bond price in the secondary market. To be certain, CDS coverage of Greek sovereign debt was very low, at less than 2%. One would not expect the outcome of the bond auction to dictate terms of the restructuring.

[14] BIS Quarterly Review, December 2010. "The Big Bang in the CDS Market"

[67] provide a detailed discussion on the determinants of U.S. sovereign CDS spread beyond credit risk. For instance, the majority of U.S. CDS contracts are denominated in euros, and there is a small foreign exchange premium embedded in the spread. U.S. dollar denominated contracts did not start trading until August 2010 and volumes are thin relative to euro contracts. Additionally, there is uncertainty in the cheapest-to-deliver option due to the bond auction protocol conditional on default occurring. Lastly, the U.S. CDS spread should contain a liquidity premium component due to the relative scarcity of the instrument compared to other sovereign CDS contracts. A combination of these factors contribute to the U.S. sovereign CDS premium.

In the context of our project, we use the U.S. sovereign CDS premium as a proxy for default risk to study the relative pricing of nominal Treasury bonds and inflation-protected bonds. We present several robustness tests in the Appendix to rule out the possibility these non-credit risk-related factors can simultaneously generate differential prices in U.S. sovereign bonds.

3.2.3 CDS-Implied LGD and Effective LGD

In practice, there can be a significant difference in the LGD faced by uncovered and covered bond position holders. This discrepancy is due to the auction process determining the LGD used for CDS purposes. Let us assume that upon trigger of a U.S. sovereign credit event, the auction determines that the reference bond is worth 75 cents per dollar, yielding an auction-based LGD of 25 cents. In the case of physical delivery, an investor holding a covered position can sell her bond at par to the protection seller and receives one dollar.

An interesting case arises for cash delivery, where the protection seller delivers 25 cents to the protection buyer but the latter holds onto her bond. The government then determines an effective LGD which can be different than 25 cents. If the effective LGD is 20 cents, the protection buyer is left with one dollar and five cents. This effect is similar to the CtD option for physical delivery and can lead the CDS-implied LGD to be greater than the effective LGD for the bond holder.

While we are aware of the existence of these complications, we leave them aside in our empirical analysis for pragmatic reasons. Our rationale is that while it is straightforward to obtain the LGD resulting from a CDS auction for past credit events, obtaining the effective LGD from these events is a task with very little, if any data. In addition, the case of a U.S. credit event has been so rare that attempting to impute any figure would be pure conjecture. It should also be noted that we use CDS spreads merely as a proxy for the default risk of the U.S. sovereign, which allows us to abstract away from these specifics and assume that the CDS exactly embeds the effective LGD determined by the government.

3.3 Empirical Analysis

In this section we test our main hypothesis that exposure to default risk may influence the relative pricing of nominal and inflation-protected sovereign obligations. Specifically, we test whether the ILS-BEI spread is related to the CDS spread. We examine variation in these quantities over the full sample period and a subperiod that does not include the financial crisis of 2007-2009.

3.3.1 Data

The spreads between breakevens and inflation-linked swaps are constructed in two steps. We use the data described in [99] and [100] for nominal and inflation-protected smoothed zero-coupon bonds respectively. The BEI variable is the difference between the former and the latter. We collect inflation swap data from Bloomberg and subtract the BEI from the swap spread to obtain our mispricing variable, the ILS-BEI spread. EUR-denominated CDS spread data are obtained from Markit. Our focus is on the five-year maturity for CDS contracts as this is the most liquid CDS tenor. Our data are sampled daily from January 2008 to October 2015 (full sample).[15]

[15] Our results are qualitatively the same when using USD-denominated CDS contracts after they began trading in 2010. While data on EUR-denominated CDS are available prior to 2008, U.S. CDS exhibit virtually

Table 3.1: **Summary Statistics**

Table 3.1 provides summary statistics for the variables used in the regression analysis. Panel A includes the full sample period from January 2008 to October 2015. Panel B is the post crisis subsample from January 2010 to October 2015. $ILS - BEI$ is the difference in the 5-year inflation swap rate and the 5-year breakeven inflation rate (Treasury-TIPS). Both $Tsy\ ZC\ Yield$ and $TIPS\ ZC\ Yield$ are for the 5-year maturity. 5-year $US\ CDS$ spreads are denominated in EUR. $LIBOR - OIS$ is the difference in the London Inter-bank Offered Rate and the overnight indexed swap rate. $HPW Noise$ follows [101]. $TIPS\ Noise$ measures average daily deviations in the real yield curve. VIX denotes the CBOE Volatility Index.

Panel A			**Full Sample**		
	Mean	SD	Min	Max	N
ILS-BEI (bps)	36	30	-1	210	1902
Infl Swap Rate	2.04	0.49	-0.57	3.31	1902
Tsy ZC Yield	1.74	0.70	0.59	3.76	1902
TIPS ZC Yield	0.06	1.04	-1.72	3.88	1902
US CDS (bps)	33	16	6	100	1902
LIBOR-OIS	0.34	0.43	0.06	3.64	1902
HPW Noise	3.51	3.50	0.72	20.47	1902
TIPS Noise	5.93	5.06	2.05	41.8	1902
VIX	21.96	10.44	10.32	80.86	1902
Panel B			**Post Crisis**		
	Mean	SD	Min	Max	N
ILS-BEI (bps)	23	10	-1	59	1403
Infl Swap Rate	2.09	0.29	1.24	2.71	1403
Tsy ZC Yield	1.45	0.51	0.59	2.79	1403
TIPS ZC Yield	-0.41	0.62	-1.72	0.83	1403
US CDS (bps)	34	12	14	63	1403
LIBOR-OIS	0.19	0.09	0.06	0.50	1403
HPW Noise	1.99	0.74	0.72	4.58	1403
TIPS Noise	4.72	1.41	2.05	7.58	1403
VIX	18.40	6.13	10.32	48.00	1403

no variation and volume in the pre-sample period and the quotes are often unchanged for weeks at a time and average between one and two basis points.

We depict the time series of U.S. sovereign credit default swap spreads and the ILS-BEI spread in Figure 3.1, panel (b). As documented in [67], CDS spreads soar to 100 basis points in the wake of the Lehman Brothers bankruptcy, timing that is similar to that of the large increase in ILS-BEI. Our conjecture is that this event, and the crisis that followed caused investors to reprice the probability of a U.S. sovereign default and the recovery on Treasury and TIPS in a default scenario. The spread is volatile in 2010-2013 before becoming quiescent from about 2014 onward. Notably, the spread spikes to more than 40 basis points in the days prior to the resolution of the the budget showdown of 2013, which threatened to lead to a U.S. sovereign default.

Summary statistics for these data are provided in Table 3.1. Over the full sample period, both the ILS-BEI and U.S. CDS spread averaged over 30 basis points (36 and 33 basis points respectively). The ILS-BEI is approximately twice as volatile as the CDS spread, ranging from -1 to 210 basis points. In contrast to the CDS spread, the ILS-BEI declines both on average and in volatility in the post-crisis period, which we define as January 1, 2010 and beyond. Thus, even in the post-crisis period, the U.S. CDS spread averages 34 basis points, considerably greater than its pre-crisis levels. The unconditional correlation between the five-year ILS-BEI and CDS is about 0.3.

Regression controls

In addition to possible fears of default risk, numerous factors may play a role in the observed ILS-BEI spread — namely, heightened counterparty credit risk associated with inflation swap transactions, liquidity concerns, increases in perceived quantities and prices of risk, and a deterioration in arbitrage capital available to deploy in financial markets. Each of these potentially confounding factors would be expected to play an outsized role influencing the components of the ILS-BEI spread at the peak of the financial crisis. We examine the role of several variables in order to investigate alternative possibilities.

HPW Noise and *TIPS Noise* serve as our measures of arbitrage capital as proposed in

[101][16]. *LIBOR-OIS* measures counterparty credit risk. The off/on the run differential in nominal bonds (*OTR Difference*) is a proxy for liquidity in these markets while the *VIX* index is often viewed as a market measure of the prevailing price of risk in financial markets. A detailed description of each variable can be found in Appendix subsection C.1.1.

3.3.2 Empirical Results

We employ panel regressions for our empirical analysis. We include the ILS-BEI spread across five tenors: 2, 3, 5, 7, and 10 years as the dependent variable. As is standard in the fixed income pricing literature, we assume that all interest rates at all maturities are second-order stationary despite a high persistence. Although stationarity tests usually fail to reject the presence of a unit root, they suffer from lack of power in small samples. In addition, it is difficult to justify that either the mean or variance of U.S. interest rates will follow an explosive path. Our baseline specification is thus given by:

$$(\mathrm{ILS}-\mathrm{BEI})_{n,t} = \alpha + \rho \cdot (\mathrm{ILS}-\mathrm{BEI})_{n,t-1} + \gamma \cdot \mathrm{CDS}_t + \boldsymbol{\beta}^{\top} \cdot \mathbf{X_t} + w_t + \varepsilon_{n,t}\,, \quad (3.2)$$

where $n = \{2, 3, 5, 7, 10\}$, $\mathbf{X_t}$ represents the set of relevant controls, and w_t is a week-time fixed effect. For ease of interpretation, we present the R^2 of this regression as the fraction of the ILS-BEI spread changes explained by our explanatory variables. This naturally brings the R^2 closer to zero, allowing us to see significant changes across specifications.

Table 3.2 shows regression results for the full sample, spanning the beginning of 2008 to October 2015. We start the sample in 2008 due to the fact that U.S. sovereign CDS contracts were thinly traded prior to the 2008 financial crisis. All regressions contain observations at the daily frequency where data is available for consecutive trading days in all markets. Columns (1) - (6) depict results with individual covariates in the specification, and column (7) represents the full multivariate specification. In column (8) we add tenor fixed effects

[16] The HPW Noise measure is sourced from Jun Pan's website and we thank Richard Crump for providing the TIPS Noise series.

to the full specification. Finally, in each regression, the U.S. CDS spread is the main explanatory variable, but we include the lagged ILS-BEI spread to ensure the persistence of the dependent variable is not driving our results.

Table 3.2: **ILS-BEI - January 2008 to October 2015**

Table 3.2 shows the results from a panel regression of ILS-BEI on US CDS spreads and various controls using daily observations. The sample period is from January 2008 to October 2015. $ILS - BEI$ is the difference in the inflation swap rate and the breakeven inflation rate (Treasury-TIPS) for 2-, 3-. 5-, 7-, and 10-year tenors. $US\ CDS$ spreads are for the 5-year tenor. $HPW Noise$ follows [101]. $TIPS\ Noise$ measures average daily deviations in the real yield curve. $LIBOR - OIS$ is the difference in the London Inter-bank Offered Rate and the overnight indexed swap rate. $OTR\ Difference$ is the difference in 10-year Treasury par yield from [99] less the on-the-run 10-year Treasury yield from Bloomberg. VIX denotes the CBOE Volatility Index. Standard errors are reported in parentheses.

Dep Var: ILS-BEI Spread	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
US CDS	0.196***	0.195***	0.218***	0.205***	0.186***	0.218***	0.228***	0.228***
	(0.049)	(0.049)	(0.049)	(0.050)	(0.049)	(0.051)	(0.051)	(0.051)
ILS-BEI$_{t-1}$	0.822***	0.822***	0.823***	0.822***	0.822***	0.822***	0.823***	0.817***
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
HPW Noise		0.111					0.637**	0.633**
		(0.283)					(0.291)	(0.290)
TIPS Noise			−1.077***				−1.039***	−1.033***
			(0.172)				(0.182)	(0.182)
LIBOR-OIS				−3.303*			−3.965**	−3.952**
				(1.826)			(1.924)	(1.921)
OTR Difference					−24.810***		−17.395***	−17.457***
					(4.816)		(5.086)	(5.076)
VIX						−0.065*	−0.023	−0.022
						(0.039)	(0.041)	(0.041)
Week	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Tenor	No	No	No	No	No	No	No	Yes
Observations	9147	9147	9147	9147	9147	9127	9127	9127
$1 - \mathbb{V}(\varepsilon_t)/\mathbb{V}[\Delta(\text{ILS}_t - \text{BEI}_t)]$	0.148	0.148	0.152	0.149	0.151	0.149	0.155	0.158

*,**,*** represent statistical significance at the 10%, 5%, and 1% critical threshold, respectively.

As shown in the top row of Table 3.2, all coefficient loadings on the U.S. CDS spread are positive and highly significant across the columns. The point estimate of 0.196 in Column (1) is statistically significant at the 1% level and suggests that a 16 basis point increase in U.S. CDS spreads (one standard deviation) translates into an approximately 3.1 basis point increase in the ILS-BEI spread. This represents approximately 10% of the mean ILS-BEI suggesting the results are economically significant as well.

Table 3.2 also demonstrates that it is essential to include lagged ILS-BEI spread as an explanatory variable since coefficient loadings are positive and highly significant regardless which control variables are used. It should not be surprising that the ILS-BEI spread is highly persistent. Amongst the control variables, LIBOR-OIS spread in Column (4), and VIX in Column (6) are marginally significant (between 5% and 10% statistical significance). The TIPS Noise measure in Column (3) and the OTR Difference in Column (5) are negative and highly significant. A higher value of TIPS Noise indicates greater deviations in the TIPS yield curve. Although we would expect this to reflect poorer liquidity on the TIPS market and thus to increase the ILS-BEI spread, we note that all liquidity measures are highly correlated and it is hard to extract a clean interpretation for each single coefficient. When all variables are included, in Column (7) of Table 3.2, the coefficient on CDS increases to 0.228 (3.6bps per CDS standard deviation), and HPW Noise becomes statistically significant. Given the high positive correlation with TIPS Noise this result is not surprising. The estimated coefficient loading on the CDS spread actually increases from Column (1) to Column (7) when controls are included. Finally, the addition of a tenor fixed effect does not affect the regression outcomes in Column (8) suggesting our results are not driven by a particular maturity on the yield curve. We present the fitting measure as one minus the ratio of unexplained variance over the variance of the first difference of ILS-BEI spreads. These spreads are highly persistent and standard R^2 measures are close to one when controlling for lagged spreads, thus barely informative. We use this measure throughout for all regressions in levels using the lagged ILS-BEI spread as a control.

Table 3.3: **First Differences of ILS-BEI - January 2008 to October 2015**

Table 3.3 shows the results from a panel regression of the change in ILS-BEI on the change in US CDS spreads and various controls using daily observations. The sample period is from January 2008 to October 2015. $ILS - BEI$ is the difference in the inflation swap rate and the breakeven inflation rate (Treasury-TIPS) for 2-, 3-. 5-, 7-, and 10-year tenors. $US\ CDS$ spreads are for the 5-year tenor. $HPWNoise$ follows [101]. $TIPS\ Noise$ measures average daily deviations in the real yield curve. $LIBOR - OIS$ is the difference in the London Inter-bank Offered Rate and the overnight indexed swap rate. $OTR\ Difference$ is the difference in 10-year Treasury par yield from [99] less the on-the-run 10-year Treasury yield from Bloomberg. VIX denotes the CBOE Volatility Index. Standard errors are reported in parentheses.

Dep Var: Δ ILS-BEI Spread	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Δ US CDS	0.154***	0.153***	0.161***	0.161***	0.141***	0.168***	0.160***	0.160***
	(0.052)	(0.052)	(0.052)	(0.052)	(0.052)	(0.052)	(0.052)	(0.052)
Δ HPW Noise		–0.402					–0.241	–0.241
		(0.254)					(0.256)	(0.256)
Δ TIPS Noise			–1.872***				–1.806***	–1.807***
			(0.205)				(0.207)	(0.207)
Δ LIBOR-OIS				–7.768***			–3.910	–3.910
				(2.713)			(2.835)	(2.836)
Δ OTR Difference					–21.738***		–16.946***	–16.946***
					(3.456)		(3.695)	(3.696)
Δ VIX						–0.097***	–0.040	–0.040
						(0.037)	(0.038)	(0.038)
Week	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Tenor	No	No	No	No	No	No	No	Yes
Observations	9142	9142	9137	9142	9142	9107	9102	9102
R^2	0.001	0.001	0.006	0.001	0.005	0.001	0.009	0.053

*,**,*** represent statistical significance at the 10%, 5%, and 1% critical threshold, respectively.

We repeat our main empirical test in first differences rather than levels to further ensure the persistence of ILS-BEI is not driving our finding and report the results in Table 3.3. Similar to Table 3.2, the change in CDS spread is shown to be a positive and significant factor driving the change in ILS-BEI in the first row. Under the full specification in Column (8), with both week and tenor fixed effects, a 1% increase in the change of CDS spread results in a 16 bps greater increase in the change of ILS-BEI after controlling for changes in the noise measures, systemic risk, liquidity and volatility. In line with Table 3.2, changes in TIPS noise and changes in OTR Differences are negative and highly significant under the full specification, suggesting the liquidity effect is present in first differences as well. Results presented in Table 3.3 should ease the concern that the relationship between CDS spread and ILS-BEI we document is purely spurious.

To check that the credit risk influence indeed stems from TIPS, we regress the components of ILS-BEI separately on U.S. CDS spread in the full sample. Table 3.4 documents the regression results. The dependent variables in columns (1), (2), and (3) are, respectively, TIPS yields, nominal Treasury yields, and ILS swap premia. To be consistent with previous tests, we employ tenors of 2-, 3-, 5-, 7-, and 10-years on all the dependent variables. The explanatory variables include the 5-year CDS spread, lagged dependent variables, as well as standard controls used in Table 3.2.

Both TIPS yields and nominal yields load positively and significantly on the CDS spread, in Columns (1) and (2), whereas the ILS spread shows no significant correlation with the CDS spread in Column (3). This suggests that the ILS-BEI spread comoves with the CDS spread because of the reaction of the real and nominal term structures to sovereign default risk. Moreover, the coefficient loading of TIPS yields on CDS is larger than the coefficient loading of nominal yields on CDS. This implies that the BEI narrows as CDS spread increase, and that the ILS-BEI spread increases.

Table 3.4: **Components of ILS-BEI Spread - January 2008 to October 2015**

Table 3.4 shows the results from a panel regression of TIPS yields, Treasury yields, and ILS spreads on US CDS spreads and various controls using daily observations. The sample period is from January 2008 to October 2015. $US\ CDS$ spreads are for the 5-year tenor. $HPW Noise$ follows [101]. $TIPS\ Noise$ measures average daily deviations in the real yield curve. $LIBOR - OIS$ is the difference in the London Inter-bank Offered Rate and the overnight indexed swap rate. $OTR\ Difference$ is the difference in 10-year Treasury par yield from [99] less the on-the-run 10-year Treasury yield from Bloomberg. VIX denotes the CBOE Volatility Index. Standard errors are reported in parentheses.

	(1)	(2)	(3)
Dep Var:	TIPS	Nominal	ILS
US CDS	0.268^{***}	0.123^{***}	0.061
	(0.047)	(0.045)	(0.061)
TIPS_{t-1}	0.985^{***}		
	(0.002)		
Nominal $_{t-1}$		0.972^{***}	
		(0.002)	
ILS $_{t-1}$			0.960^{***}
			(0.003)
HPW Noise	-0.735^{***}	-1.910^{***}	−0.489
	(0.266)	(0.254)	(0.345)
TIPS Noise	-1.750^{***}	−0.009	0.541^{**}
	(0.167)	(0.159)	(0.216)
LIBOR-OIS	-28.185^{***}	-20.507^{***}	3.139
	(1.762)	(1.684)	(2.281)
OTR Difference	-19.114^{***}	-22.629^{***}	-20.587^{***}
	(4.651)	(4.449)	(6.026)
VIX	0.077^{**}	-0.454^{***}	-0.568^{***}
	(0.037)	(0.036)	(0.048)
Week	Yes	Yes	Yes
Tenor	Yes	Yes	Yes
Observations	9130	9130	9130
$1 - \mathbb{V}(\varepsilon_t)/\mathbb{V}[\Delta(\text{ILS}_t - \text{BEI}_t)]$	0.290	0.249	0.176

*,**,*** represent statistical significance at the 10%, 5%, and 1% critical threshold, respectively.

Results shown in Table 3.4 provide some comfort that the CDS spread is indeed producing differential impact on sovereign bond yields and not on the inflation swap. This is crucial evidence that sovereign default risk can impact the relative pricing of TIPS and nominal bonds.

3.3.3 Sub-sample Analysis

We examine the degree to which the 2008 financial crisis influences our conclusions by separating the sample into a crisis period, which we specify as January, 2008 through December, 2009, and a post-crisis period from January, 2010 onward. Results for the crisis period are presented in Table 3.5. Our results carry through during the crisis sample. Depending on the specification, CDS coefficients range from 0.20 to 0.27. Although their statistical significance is weaker (5-10% level) during the crisis period relative to the full sample, the point estimates on the U.S. CDS spread are greater, which implies a more pronounced effect between sovereign default risk and first differences in the ILS-BEI spread.

For the post-crisis period, the results depicted in Table 3.6 are essentially unchanged as well. Again, depending on the specification, CDS coefficients range from 0.16 to 0.17 and are significant at the 1% level, indicating more precise estimates than in the crisis sample. The point estimates across all columns are roughly five times greater than their standard errors.

Table 3.5: **ILS-BEI - January 2008 to December 2009**

Table 3.5 shows the results from a panel regression of ILS-BEI on US CDS spreads and various controls using daily observations. The sample period is from January 2008 through December 2009. $ILS - BEI$ is the difference in the inflation swap rate and the breakeven inflation rate (Treasury-TIPS) for 2-, 3-. 5-, 7-, and 10-year tenors. $US\ CDS$ spreads are for the 5-year tenor. $HPW Noise$ follows [101]. $TIPS\ Noise$ measures average daily deviations in the real yield curve. $LIBOR - OIS$ is the difference in the London Inter-bank Offered Rate and the overnight indexed swap rate. $OTR\ Difference$ is the difference in the on-the-run 10-year U.S. Treasury and the off-the-run 9-year U.S. Treasury from the Bloomberg on/off-the-run U.S. Treasury curve. VIX denotes the CBOE Volatility Index. Standard errors are reported in parentheses.

Dep Var: ILS-BEI Spread	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
US CDS	0.213*	0.209*	0.258**	0.232*	0.199*	0.258**	0.270**	0.264**
	(0.120)	(0.121)	(0.121)	(0.122)	(0.120)	(0.124)	(0.125)	(0.121)
ILS-BEI$_{t-1}$	0.795***	0.795***	0.796***	0.795***	0.795***	0.796***	0.797***	0.698***
	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)	(0.013)
HPW Noise		0.364					1.246*	1.091*
		(0.631)					(0.660)	(0.636)
TIPS Noise			–1.139***				–1.011***	–0.886***
			(0.321)				(0.354)	(0.341)
LIBOR-OIS				–3.374			–3.272	–3.001
				(3.256)			(3.594)	(3.462)
OTR Difference					–44.458***		–32.578***	–34.241***
					(11.188)		(12.240)	(11.792)
VIX						–0.151	–0.072	–0.055
						(0.098)	(0.106)	(0.102)
Week	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Tenor	No	No	No	No	No	No	No	Yes
Observations	2387	2387	2387	2387	2387	2387	2387	2387
$1 - \mathbb{V}(\varepsilon_t)/\mathbb{V}[\Delta(\text{ILS}_t - \text{BEI}_t)]$	0.168	0.168	0.172	0.168	0.173	0.168	0.177	0.238

*,**,*** represent statistical significance at the 10%, 5%, and 1% critical threshold, respectively.

Table 3.6: **ILS-BEI - January 2010 to October 2015**

Table 3.6 shows the results from a panel regression of ILS-BEI on US CDS spreads and various controls using daily observations. The sample period is from January 2010 to October 2015. $ILS - BEI$ is the difference in the inflation swap rate and the breakeven inflation rate (Treasury-TIPS) for 2-, 3-. 5-, 7-, and 10-year tenors. $US\ CDS$ spreads are for the 5-year tenor. $HPWNoise$ follows [101]. $TIPS\ Noise$ measures average daily deviations in the real yield curve. $TIPSNoise$ measures average daily deviations in the real yield curve. $LIBOR - OIS$ is the difference in the London Inter-bank Offered Rate and the overnight indexed swap rate. $OTR\ Difference$ is the difference in 10-year Treasury par yield from [99] less the on-the-run 10-year Treasury yield from Bloomberg. VIX denotes the CBOE Volatility Index. Standard errors are reported in parentheses.

Dep Var: ILS-BEI Spread	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
US CDS	0.171***	0.170***	0.172***	0.171***	0.172***	0.164***	0.165***	0.167***
	(0.035)	(0.035)	(0.035)	(0.035)	(0.035)	(0.037)	(0.037)	(0.037)
ILS-BEI_{t-1}	0.905***	0.905***	0.905***	0.905***	0.905***	0.904***	0.904***	0.888***
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.006)
HPW Noise		–0.396*					–0.381*	–0.376
		(0.230)					(0.231)	(0.230)
TIPS Noise			–0.415				–0.377	–0.375
			(0.268)				(0.270)	(0.269)
LIBOR-OIS				–4.591			–3.509	–3.280
				(7.704)			(7.769)	(7.739)
OTR Difference					1.563		2.120	2.056
					(3.667)		(3.737)	(3.723)
VIX						0.022	0.018	0.020
						(0.028)	(0.028)	(0.028)
Week	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Tenor	No	No	No	No	No	No	No	Yes
Observations	6755	6755	6755	6755	6755	6735	6735	6735
$1 - \mathbb{V}(\varepsilon_t)/\mathbb{V}[\Delta(\text{ILS}_t - \text{BEI}_t)]$	0.100	0.101	0.101	0.101	0.101	0.101	0.102	0.109

*,**,*** represent statistical significance at the 10%, 5%, and 1% critical threshold, respectively.

Our interpretation of these results is that determinants of the U.S. CDS spread comove strongly with daily changes in ILS-BEI. While CDS spreads may be driven by a number of different factors, including actual default risk and liquidity effects, we view the evidence here as sufficiently suggestive to indicate ILS-BEI is influenced by credit risk. The relationship appears to persist during periods of high volatility and strained financial conditions (crisis) as well under conditions associated with normally functioning markets.

3.3.4 Default Risk and Liquidity

[86] suggest that much of the spread between nominal and inflation-protected bond yields arises as a premium for liquidity. In their analysis, they find that the portion of breakeven inflation that is related to liquidity rather than inflation expectations accounts on average for 69bps of the spread between nominal and inflation-protected securities. While we endeavor to control for liquidity in our earlier analysis, in this section we explicitly examine the contribution of CDS to the liquidity premium that they document.

The authors measure the liquidity premium by breaking the differential in the yield on nominal and inflation-protected securities on a set of liquidity variables and measures of inflation expectations:

$$\mathrm{BEI}_t^{(n)} = a_1 + \mathbf{a}_2^\top \mathbf{X}_t + \mathbf{a}_3^\top \boldsymbol{\pi}_t^e + \varepsilon_{n,t}, \tag{3.3}$$

where $\mathbf{X}_t$ is a vector of liquidity-related variables and $\boldsymbol{\pi}_t^e$ is a vector of measures of inflation expectation. The liquidity premium is measured as $\hat{L}_t = -\hat{\mathbf{a}}_2^\top \mathbf{X}_t$. We follow their approach, using the breakeven inflation between 10-year nominal and inflation-protected securities as our dependent variable. We describe the independent variables in Appendix subsubsection C.1.2. One key point is that the liquidity variables $\mathbf{X}_t$ include the ILS-BEI spread as a proxy.

Results of the analysis are presented in Table 3.7. In the first column of Panel A, we present an analysis complementary to that of [86]. Consistent with their analysis, and with intuition, inflation expectation variables are positively related to breakeven inflation. The coefficient on the ILS-BEI is negative; the authors interpret the result as suggesting that the pronounced decrease in breakeven inflation during the financial crisis reflected security market disruption and constraints on levered investors. The authors find that one cannot reject the hypothesis that the coefficient is equal to negative one. However, in our results, the point estimate of the coefficient is more than two standard errors from one. This result suggests that, consistent with our results above, the ILS-BEI may reflect more than just constraints on levered market participants.

In the second column, we add the CDS spread to the regression. Three observations emerge. First, the CDS spread is negatively and significantly related to breakeven inflation. To the extent that default risk may have differential impact on nominal and inflation-protected Treasury securities, the negative coefficient suggests that yield spreads on the two securities tighten when default risk increases. This may reflect a flight to the relative safety of nominal Treasuries or a drop in the prices of inflation-protected securities. Second, the coefficients on the remaining variables, with the exception of ILS-BEI, are materially unaffected. Third, after controlling for CDS, one can no longer reject the hypothesis that the coefficient on the ILS-BEI is equal to negative one, consistent with the results in [86]. Thus, the results indicate that both the BEI and the ILS-BEI reflect co-movement with CDS spreads due to credit risk.

Table 3.7: **Liquidity Premia and CDS**

Table 3.7 presents results of an analysis of liquidity premia. In Panel A, we present results from regressions

$$
\begin{aligned}
BEI_t &= a_1 + a_2 OTR_t + a_3 VOL_t + a_4 ILS - BEI_t + a_5 CPI_t^e + a_6 CFNAI_t + \epsilon_{1t} \\
BEI_t &= b_1 + b_2 OTR_t + b_3 VOL_t + b_4 ILS - BEI_t + b_5 CPI_t^e + b_6 CFNAI_t + b_7 US\,CDS_t + \epsilon_{2t},
\end{aligned}
$$

where the dependent variable is breakeven inflation, and the independent variables are OTR, the on-the-run 10-Year Treasury Spread, VOL, the log ratio of volume in the TIPS market to the nominal Treasury market, $ILS - BEI$, the inflation swap-adjusted BEI, CPI^e, the median forecast of 10-year CPI inflation from the Survey of Professional Forecasters, $CFNAI$, the Chicago Fed National Activity Index, and $US\,CDS$, the 5-year credit default swap spread for U.S. Treasury securities. In Panel B, the estimated liquidity premium from Panel A is regressed on the U.S. CDS spread. The liquidity premium is measured as

$$\hat{L}_t = -\left(\hat{a}_2 OTR_t + \hat{a}_3 VOL_t + \hat{a}_4 ILS - BEI_t\right).$$

Newey-West standard errors are reported in parentheses.

Panel A: Breakeven Inflation

Dep Var: BEI	(1)	(2)
OTR	–1.143**	–1.218***
	(0.153)	(0.155)
VOL	–0.438***	–0.472***
	(0.058)	(0.060)
$ILS - BEI$	–1.284***	–1.158***
	(0.103)	(0.109)
CPI^e	0.960***	0.997***
	(0.109)	(0.106)
$CFNAI$	0.027*	0.031**
	(0.014)	(0.014)
$US\,CDS$		–0.214***
		(0.075)
R^2	0.651	0.656

Panel B: Liquidity Premium

Dep Var: $\hat{L}$	
$US\,CDS$	0.608***
	(0.126)
R^2	0.086

Notes: *,**,*** represent statistical significance at the 10%, 5%, and 1% critical threshold, respectively.

Our final analysis of the liquidity premium directly regresses the estimated liquidity premium on the CDS spread. Results are presented in Panel B. As shown in the Table, CDS spreads on Treasury securities are positively and statistically significantly related to the liquidity premium, explaining approximately 9% of its variation. This result suggests that part of the liquidity premium documented in [86] may in fact reflect compensation for credit risk. However, the majority of the variation in the premium is unrelated to variation in CDS spreads, indicating that both liquidity and credit risk jointly play a role in understanding the x pricing of TIPS and nominal Treasury securities.

3.3.5 United Kingdom Evidence on Default Risk and Bond Pricing

In this section, we validate our hypothesis in the international setting. The United Kingdom was one of the first major developed markets to introduced inflation-linked bonds in 1981. These "linkers" are much like TIPS in the U.S. in that their principal and coupons are contractually linked to a domestic price index acting as real bonds in contrast to U.K. gilts. Thus, much as we see different responses in U.S. nominal and real yields to default risk, we expect similar patterns in the relation between hedged gilts, linkers, and CDS spreads in the U.K. For the U.K. analysis, we focus only on the post crisis period because the subsample analysis in subsection 3.3.3 shows that the relationship between ILS-BEI and CDS spread is statistically stronger after 2009. This means the impact of sovereign credit risk on bond yields is not a crisis period phenomenon.

We obtain U.K. yield data from the Bank of England's website and CDS spreads from Markit. We perform the same panel regressions as those in Table 3.6 by pooling yields across tenors at the daily frequency for the post-financial crisis sample period from January 2010 to October 2015. Where data are available, we utilize U.K. control variables similar to those employed in our U.S. analysis. Specifically, we control for the off/on the run differential in nominal bonds, GBP LIBOR-OIS spread, and VSTOXX index (Euro Stoxx 50 volatility index), but do not have access to data for a measure comparable to the HPW noise variable.

Regression results for the U.K. are reported in Table 3.8. We control for lagged ILS-BEI just as we have done for the U.S. In Column (1), we see U.K. CDS spread is positive and significantly related to contemporaneous ILS-BEI. A one percent increase in the CDS spread translates to a 10 bps widening of the ILS-BEI. The magnitude of the coefficient on U.K. CDS declines to about 7 bps in Column (5) with the VSTOXX index as a control. Results in the full specification in Column (6) remain little changed. The U.K. results are consistent with those in Table 3.6 for the U.S.: higher default risk as proxied by larger CDS spread leads to a widening of the ILS-BEI in the data.

Table 3.9 presents the U.K. regression results in first differences rather than in levels. These regressions mirror those shown in Table 3.3 for the U.S. The dependent variable is the one-period change in the U.K. ILS-BEI, and the main explanatory variable is the one-period change in the U.K. CDS spread. All control variables are also employed in first differences. In Column (1), a larger innovation in the CDS spread implies a greater increase in the ILS-BEI. The estimated coefficient is statistically significant at the 1% level. The statistical significance in the first row remains in subsequent columns as control variables are added in first differences. In Column (6) of Table 3.9, with all the controls as well as both week and tenor fixed effects, the change in U.K. ILS-BEI still loads positive and significantly on the change in U.K. CDS spread. Overall, our U.K. findings corroborate with those in the U.S.: higher sovereign default risk leads to a narrowing of the risky break even inflation as real bonds decline more in price than nominal bonds.

Table 3.8: **United Kingdom ILS-BEI Spread - January 2010 to October 2015**

Table 3.8 shows the results from a panel regression of the change in UK ILS-BEI spreads on the changes in UK CDS spreads and various controls using daily observations. The sample period is from January 2010 to October 2015. $UK\ CDS$ spreads are for the 5-year tenor. $LIBOR - OIS$ is the difference in the GBP London Inter-bank Offered Rate and the overnight indexed swap rate. $OTR\ Difference$ is the difference in 10-year yield from the Bank of England website less the on-the-run 10-year gilt yield from Bloomberg. $VSTOXX$ denotes the EURO STOXX 50 Volatility Index. Standard errors are reported in parentheses.

Dep Var: UK ILS-BEI Spread	(1)	(2)	(3)	(4)	(5)	(6)
UK CDS	0.112^{***}	0.106^{***}	0.116^{***}	0.074^{***}	0.072^{***}	0.072^{***}
	(0.024)	(0.024)	(0.024)	(0.027)	(0.027)	(0.027)
UK ILS-BEI$_{t-1}$	0.966^{***}	0.966^{***}	0.966^{***}	0.965^{***}	0.965^{***}	0.953^{***}
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)
OTR Difference		-18.497^{***}			-18.605^{***}	-18.866^{***}
		(4.032)			(4.044)	(4.033)
GBP LIBOR-OIS			-20.424^{***}		-20.543^{***}	-20.000^{**}
			(7.885)		(7.915)	(7.895)
VSTOXX				0.097^{***}	0.102^{***}	0.103^{***}
				(0.032)	(0.032)	(0.032)
Week	Yes	Yes	Yes	Yes	Yes	Yes
Tenor	No	No	No	No	No	Yes
Observations	6482	6482	6482	6427	6427	6427
$1 - \mathbb{V}(\varepsilon_t)/\mathbb{V}[\Delta(\mathrm{ILS}_t - \mathrm{BEI}_t)]$	0.137	0.140	0.138	0.140	0.144	0.149

*,**,*** represent statistical significance at the 10%, 5%, and 1% critical threshold, respectively.

Table 3.9: **First Difference of United Kingdom ILS-BEI Spread - January 2010 to October 2015**

Table 3.9 shows the results from a panel regression of the change in UK ILS-BEI spreads on the changes in UK CDS spreads and various controls using daily observations. The sample period is from January 2010 to October 2015. $UK\ CDS$ spreads are for the 5-year tenor. $LIBOR - OIS$ is the difference in the GBP London Inter-bank Offered Rate and the overnight indexed swap rate. $OTR\ Difference$ is the difference in 10-year yield from the Bank of England website less the on-the-run 10-year gilt yield from Bloomberg. $VSTOXX$ denotes the EURO STOXX 50 Volatility Index. Standard errors are reported in parentheses.

Dep Var: Δ UK ILS-BEI Spread	(1)	(2)	(3)	(4)	(5)	(6)
Δ UK CDS	0.266***	0.267***	0.240***	0.218***	0.192***	0.192***
	(0.026)	(0.026)	(0.026)	(0.030)	(0.030)	(0.030)
Δ GBP LIBOR-OIS		−6.748			−7.602	−7.597
		(8.754)			(8.708)	(8.711)
Δ OTR Difference			−34.044***		−35.042***	−35.04***
			(3.209)		(3.226)	(3.227)
Δ VSTOXX				0.106***	0.108***	0.108***
				(0.030)	(0.030)	(0.030)
Week	Yes	Yes	Yes	Yes	Yes	Yes
Tenor	No	No	No	No	No	Yes
Observations	6366	6366	6366	6299	6299	6299
R^2	0.138	0.138	0.154	0.141	0.158	0.158

*,**,*** represent statistical significance at the 10%, 5%, and 1% critical threshold, respectively.

3.4 Modeling Nominal and Inflation-Protected Debt with Default Risk

In this section, we discuss the pricing of nominal and inflation-protected sovereign bonds, assuming that there is a possibility of a credit event interrupting the promised payments of the securities. Of particular interest is the spread between inflation-linked swaps and the breakeven inflation rate. We develop a new affine pricing model to complement panel regression results in subsection 3.3.2. With the aid of the model, we decompose the ILS-BEI spread into its credit and liquidity components to examine the dynamic contribution of the credit factors during the after the crisis.

3.4.1 Riskless yields dynamics

Let us consider a vector of N_x unobservable factors, denoted by x_t. We assume these factors have standard Gaussian VAR dynamics such that:

$$x_t = \mu + \Phi x_{t-1} + \sqrt{\Sigma}\varepsilon_t \quad \text{where} \quad \varepsilon_t \overset{i.i.d}{\sim} \mathcal{N}\left(0,\, I_{N_x}\right) \,. \tag{3.4}$$

In this economy, there exists a riskless nominal asset trading at date t at price e^{-r_t} and delivering one unit of cash at $t+1$. We assume that the riskless nominal yield is given by a linear combination of x_t:

$$r_t = \kappa_0^{(r)} + \kappa_x^{(r)\prime} x_t \,, \tag{3.5}$$

where $\kappa_0^{(r)}$ is a scalar and $\kappa_x^{(r)}$ is a vector of size N_x. The term structure of riskless nominal yields will therefore be entirely driven by x_t. These yields will in turn constitute our discount rates for the remaining nominal securities (see for instance [102]).

3.4.2 Default and liquidity dynamics

Our modeling framework follows that of [70] in modeling risky debt in discrete time. In their framework, sovereign credit events of any kind are represented by jumps of a non-negative credit-event variable denoted by $\delta_t^{(c)}$. Our modeling of liquidity events on the TIPS market mimics the form employed for credit events (see e.g. [103], [104] or [105]). We assume that liquidity events on the TIPS market are represented by jumps of a liquidity-event variable denoted by $\delta_t^{(\ell)}$. More formally, the times of credit and liquidity events, τ_c and τ_ℓ, can be defined as:

$$\tau_c = \min\left\{ t \,|\, \delta_t^{(c)} > 0 \right\} \quad \text{and} \quad \tau_\ell = \min\left\{ t \,|\, \delta_t^{(\ell)} > 0 \right\}. \tag{3.6}$$

Note that, since we do not observe any default event during our sample, the time series of $\delta_t^{(c)}$ will be uniformly zero throughout the sample. We assume the same for the liquidity event variable $\delta_t^{(\ell)}$ for simplicity.[17] The probabilities of credit and liquidity events are driven by the default and liquidity intensities $\lambda_t^{(c)}$ and $\lambda_t^{(\ell)}$, respectively. We assume that the credit- and liquidity-event variables are Gamma-zero distributed given their respective intensities. That is, there exist Poisson distributed random variables $\mathsf{P}_t^{(c)}$ and $\mathsf{P}_t^{(\ell)}$ such that:[18]

$$\begin{cases} \mathsf{P}_t^{(c)} \,|\, \lambda_t^{(c)} \sim \mathcal{P}\left(\lambda_t^{(c)}\right) & \text{and} \quad \delta_t^{(c)} \,|\, \mathsf{P}_t^{(c)} \sim \Gamma_{\mathsf{P}_t^{(c)}}\left(\mathsf{c}_\delta^{(c)}\right), \\ \mathsf{P}_t^{(\ell)} \,|\, \lambda_t^{(\ell)} \sim \mathcal{P}\left(\lambda_t^{(\ell)}\right) & \text{and} \quad \delta_t^{(\ell)} \,|\, \mathsf{P}_t^{(\ell)} \sim \Gamma_{\mathsf{P}_t^{(\ell)}}\left(\mathsf{c}_\delta^{(\ell)}\right), \end{cases} \tag{3.7}$$

where $\mathsf{c}_\delta^{(c)}$ and $\mathsf{c}_\delta^{(\ell)}$ are positive scaling parameters, and $\mathsf{P}_t^{(c)}$ and $\mathsf{P}_t^{(\ell)}$ are the degree of freedom parameters, at date t, of the associated gamma distribution. With the assumption of Equation (Equation 3.7), it is easy to see that the survival probabilities are respectively given by $e^{-\lambda_t^{(c)}}$ and $e^{-\lambda_t^{(\ell)}}$. [70] show that Gamma-zero processes are efficient in representing credit events since they can stay at the value of zero for extended periods of time (no default or liquidity states) and jump to any positive value upon events. In the following, we use the notation $\delta_t = \left(\delta_t^{(c)},\, \delta_t^{(\ell)}\right)'$ and $\Gamma_0\left(\lambda_t,\, \mathsf{c}_\delta\right)$ for the Gamma-zero distribution.

Staying true to the spirit of affine models, we assume that credit and liquidity inten-

[17] Note that, this makes it harder for the model to fit the TIPS yields, if anything. Indeed, by imposing that $\delta_t^{(\ell)} = 0$ during our sample, we effectively suppress one factor for the fit.

[18] See [106] for details on the gamma-zero process.

sities are linearly related to N_c and N_ℓ vectors of state variables, denoted by $y_t^{(c)}$ and $y_t^{(\ell)}$ respectively. :

$$\lambda_t^{(c)} = \beta_\lambda^{(c)\prime} y_t^{(c)} \qquad \text{and} \qquad \lambda_t^{(\ell)} = \beta_\lambda^{(\ell)\prime} y_t^{(\ell)}\,, \tag{3.8}$$

where $\beta_\lambda^{(c)}$ and $\beta_\lambda^{(\ell)}$ are vectors of non-negative entries with size N_c and N_ℓ, respectively. To ensure that these intensities are positive, we assume that the vector $y_t = \left(y_t^{(c)\prime},\, y_t^{(\ell)\prime}\right)^\prime$ of size $N_y = N_c + N_\ell$ is a vector autoregressive gamma process:

$$y_t \,\middle|\, y_{t-1} \sim \Gamma_\nu\left(\beta_y\, y_{t-1}; \mathsf{c}_y\right)\,, \tag{3.9}$$

where ν is the vector of N_y positive degree of freedom parameters, c_y is a vector of N_y positive scaling parameters, and β_y is a $N_y \times N_y$ matrix with non-negative entries representing the potential Granger causality between the credit and liquidity components of y_t.

The risk factors x_t, y_t and δ_t constitute the entirety of state variables in this economy. [70] show that the stacked vector $w_t = (x_t^\prime,\, y_t^\prime,\, \delta_t^\prime)^\prime$ of size $N = N_x + N_y + 2$ is affine, such that its conditional moment-generating function is exponential-affine and that it follows a semi-strong heteroskedastic VAR:

$$w_t = \Psi_0 + \Psi w_{t-1} + \sqrt{\Omega_{t-1}}\,\xi_t, \tag{3.10}$$

where ξ_t is a martingale difference with unit variance, and Ψ_0, Ψ and Ω_{t-1} are detailed in Appendix subsection C.1.3.

3.4.3 Inflation dynamics

In our economy, agents have access to inflation-indexed assets that compensate them for inflation fluctuations. We assume that inflation π_t is defined by the monthly log variation of the unadjusted consumer price index (CPI-U) between $t-1$ and t. Its dynamics are given by:

$$\pi_t = \kappa_0^{(\pi)} + \kappa_x^{(\pi)\prime} x_t + \kappa_y^{(\pi)\prime} y_t^{(c)} + \kappa_\delta^{(\pi)} \delta_t^{(c)} \,, \tag{3.11}$$

where $\kappa_0^{(\pi)}$ is a scalar, $\kappa_x^{(\pi)}$ and $\kappa_y^{(\pi)}$ are vectors of size N_x, and N_c, respectively, and $\kappa_\delta^{(\pi)}$ is a scalar. Our specification for inflation contains three key components. First, inflation has a Gaussian component $\kappa_x^{(\pi)\prime} x_t$, mimicking the standard affine term structure models for TIPS (see e.g. [107]). Second, our inflation process depends on the factors driving the default intensity through $\kappa_y^{(\pi)\prime} y_t^{(c)}$, allowing to capture its possible correlation with distance to default. In particular, the possibility of inflating away the debt would translate into significant components of $\kappa_y^{(\pi)}$. Last, the specification of Equation (Equation 3.11) allows for a hyperinflation or deflation jump upon default when $\kappa_\delta^{(\pi)}$ is positive or negative, respectively, reproducing the potential stigma associated with sovereign default.

3.4.4 The stochastic discount factor

We assume that no-arbitrage holds such that there exists a (nominal) stochastic discount factor M_{t+1} associated with the representative investor in this economy. We assume that its specification is given by:

$$\begin{aligned} M_{t+1} = \exp\Bigg(-r_t + \theta_{x,t}' \, \varepsilon_{t+1} + \theta_y' y_{t+1} - \frac{1}{2}\theta_{x,t}' \, \Sigma \, \theta_{x,t} - \left[\frac{\operatorname{diag}(\theta_y)\mathsf{c}_y}{\mathbf{1} - \operatorname{diag}(\theta_y)\mathsf{c}_y} \right]' \beta_y \, y_t \\ + \nu' \log\left[\mathbf{1} - \operatorname{diag}(\theta_y)\mathsf{c}_y\right], \end{aligned} \tag{3.12}$$

where $\theta_{x,t} = \theta_{0,x} + \Theta_x \, x_t$, each component of θ_y is in $(0, 1/\mathsf{c}_y)$, and the last three terms appear such that the no-arbitrage relationship $\mathbb{E}_t(M_{t+1}) = e^{-r_t}$ is verified. We show in Appendix subsection C.1.4 that this stochastic discount factor is structure-preserving, such that the classes of distribution are the same, with shifted parameters. More specifically, we still have that $\delta_t \overset{\mathbb{Q}}{\sim} \Gamma_0\left(\lambda_t, \, \mathsf{c}_\delta\right)$, the riskless factors x_t follow a Gaussian VAR given by:

$$x_t = \mu^{\mathbb{Q}} + \Phi^{\mathbb{Q}} x_{t-1} + \sqrt{\Sigma} \, \varepsilon_t^{\mathbb{Q}} \quad \text{where} \quad \varepsilon_t^{\mathbb{Q}} \overset{i.i.d.}{\sim} \mathcal{N}\left(0, \, I_{N_x}\right) , \tag{3.13}$$

and the credit and liquidity factors have modified vector autoregressive gamma dynamics, such that:

$$y_t \,\big|\, y_{t-1} \overset{\mathbb{Q}}{\sim} \Gamma_\nu \left(\beta_y^{\mathbb{Q}}\, y_{t-1}; \mathsf{c}_y^{\mathbb{Q}}\right) \,. \tag{3.14}$$

The transition between risk-neutral and physical parameters is closed-form and given by:

$$\mu^{\mathbb{Q}} = \mu + \Sigma\,\theta_{0,x}, \quad \Phi^{\mathbb{Q}} = \Phi + \Sigma\,\Theta_x, \quad \beta_y^{\mathbb{Q}} = \beta_y \operatorname{diag}\left(\frac{\mathbf{1}}{\mathbf{1} - \operatorname{diag}(\theta_y)\,\mathsf{c}_y}\right), \quad \mathsf{c}_y^{\mathbb{Q}} = \frac{\mathsf{c}_y}{\mathbf{1} - \operatorname{diag}(\theta_y)\,\mathsf{c}_y} \,. \tag{3.15}$$

For all asset prices and yields below, we will have to compute the risk-neutral expectation of exponential-affine combinations of w_t, that is of x_t, y_t and δ_t. For convenience, using the properties of affine processes, we introduce the following notation:

$$\mathbb{E}_t^{\mathbb{Q}}\left[\exp\left(u' \sum_{j=1}^{n-1} w_{t+j} + v'\, w_{t+n}\right)\right] =: \exp\left[\mathcal{A}_n^{\mathbb{Q}}(u,v) + \mathcal{B}_n^{\mathbb{Q}}(u,v)'\, w_t\right] \,, \tag{3.16}$$

where $u \in \mathbb{R}^N$ and $v \in \mathbb{R}^N$ are two arguments that will vary depending on the asset to price, and $\mathcal{A}_n^{\mathbb{Q}}(u,v)$ and $\mathcal{B}_n^{\mathbb{Q}}(u,v)$ are parametric functions that depend on all risk-neutral parameters. These function are detailed in Appendix subsection C.1.4.

3.4.5 The term structure of riskless yields

In our economy, the representative investor has access to riskless nominal and real zero-coupon bonds providing one unit of cash and one consumption unit at maturity, respectively. Nominal zero-coupon bonds with residual maturity n trade at time t at price $D_t^{(n)}$, such that $D_t^{(1)} = e^{-r_t}$. Real bonds issued at date t trade at price $D_t^{*(n)}$ and provide the compounded inflation $e^{\sum_{j=1}^{n} \pi_{t+j}}$ at date $t+n$. In our framework, both nominal and real riskless bond prices are closed-form functions of the state vector. Denoting by $\kappa^{(r)}$ and $\kappa^{(\pi)}$ the size-N vectors such that $r_t = \kappa_0^{(r)} + \kappa^{(r)\prime} w_t$ and $\pi_t = \kappa_0^{(\pi)} + \kappa^{(\pi)\prime} w_t$, we show in

Appendix subsection C.1.5 that:

$$\begin{aligned} D_t^{(n)} &= \exp\left\{-n\kappa_0^{(r)} + \mathcal{A}_n^{\mathbb{Q}}\left(-\kappa^{(r)}, \mathbf{0}\right) + \left[\mathcal{B}_n^{\mathbb{Q}}\left(-\kappa^{(r)}, \mathbf{0}\right) - \kappa^{(r)}\right]' w_t\right\} \\ D_t^{*(n)} &= \exp\left\{-n\left(\kappa_0^{(r)} - \kappa_0^{(\pi)}\right) + \mathcal{A}_n^{\mathbb{Q}}\left(\kappa^{(\pi)} - \kappa^{(r)}, \kappa^{(\pi)}\right) + \left[\mathcal{B}_n^{\mathbb{Q}}\left(\kappa^{(\pi)} - \kappa^{(r)}, \kappa^{(\pi)}\right) - \kappa^{(r)}\right]' w_t\right\}. \end{aligned} \tag{3.17}$$

Note that due to our distributional assumptions and the fact that r_t is a function of x_t only, riskless nominal bond prices are functions of x_t (identifying x_t as "riskless" factors), while real riskless bond prices can be a function of the credit risk factors $y_t^{(c)}$ through the inflation specification. Equation (Equation 3.17) produces two key features of our model for riskless yields. First, both nominal and real yields are affine functions of w_t, thus the model is an affine term structure model (ATSM). Second, zero-coupon inflation swap rates are also closed-form affine functions of w_t, given by:

$$\mathrm{ILS}_t^{(n)} = \kappa_0^{(\pi)} + \frac{\mathcal{A}_n^{\mathbb{Q}}\left(\kappa^{(\pi)} - \kappa^{(r)}, \kappa^{(\pi)}\right) - \mathcal{A}_n^{\mathbb{Q}}\left(-\kappa^{(r)}, \mathbf{0}\right)}{n} + \frac{\mathcal{B}_n^{\mathbb{Q}}\left(\kappa^{(\pi)} - \kappa^{(r)}, \kappa^{(\pi)}\right)' - \mathcal{B}_n^{\mathbb{Q}}\left(-\kappa^{(r)}, \mathbf{0}\right)'}{n} w_t\,. \tag{3.18}$$

3.4.6 Recovery assumptions

While the representative investor has access to the riskless assets presented above, she can also invest in nominal and real Treasuries (TIPS) issued by the sovereign government. We assume both types of Treasuries are subject to credit risk, while only TIPS are subject to liquidity risk for simplicity. Before turning to their respective pricing, we detail the recovery earned by the owner of each bond for both types of events.

Upon the trigger of a credit event ($\delta_{\tau_c}^{(c)} > 0$), we assume that both nominal bonds and TIPS are terminated, so that there is no selective default. We assume that the most likely situation in case of a credit event in the U.S. is that debt will be restructured, in a similar fashion to what happened in Greece in 2012. Thus, in this case, the U.S. government will offer investors to exchange the face value of outstanding bonds, nominal or inflation-indexed, against the same face value of a newly issued reference bond. While we cannot know *ex-ante* what this (or these) reference bond(s) are, we choose a nominal bond of maturity n_r, where n_r is longer than most traded sovereign bonds. In practice, we will set $n_r = 20$ years. A bond with long maturity will produce a low enough price such that most investors will suffer a significant loss given default by being to exchange short duration bonds against ones with a longer duration.

The reference bond has value $\mathcal{P}_t^{(n_r)}$ at date t, and features recovery of market value in case of a credit event (see [108]), with recovery rate $e^{-\delta_t^{(c)}}$. This means that at time of default, the credit-event variable $\delta_t^{(c)}$ jumps up by a magnitude representing the loss given default of the reference bond. [70] show that the price can be expressed as:

$$\mathcal{P}_t^{(n_r)} = \exp\left\{-n_r\kappa_0^{(r)} + \mathcal{A}_{n_r}^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathbf{e}_c, -\mathbf{e}_c\right) + \left[\mathcal{B}_{n_r}^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathbf{e}_c, -\mathbf{e}_c\right) - \kappa^{(r)} - \mathbf{e}_c\right]' w_t\right\}, \tag{3.19}$$

where $\mathbf{e}_c$ is the vector such that $\delta_t^{(c)} = \mathbf{e}_c' w_t$. We will write $B_t^{(n_r)} =: \exp\left(\mathsf{A}_{n_r} + \mathsf{B}_{n_r}' w_t\right)$ in the following sections.

For other nominal Treasuries of maturity n, we assume that the payment in case of a credit event is exactly $\mathcal{P}_{\tau_c}^{(n_r)}$, such that face values get exchanged one-for-one. For TIPS, we assume that the sovereign government can disindex the face value from realized past inflation, either partially or fully. We denote by $\rho^* \in (0, 1)$ the parameter controlling the degree of indexation of TIPS, such that the recovery payment of TIPS are given by $\exp\left(\rho^* \sum_{j=t+1}^{\tau_c} \pi_j\right)\mathcal{P}_{\tau_c}^{(n_r)}$, for a bond issued at date t. If $\rho^* = 1$, there is full indexation and the sovereign government fully honors inflation compensation. In turn, if $\rho^* = 0$, there is full disindexation and the government completely forgives inflation indexation, in which case the recovery payment for nominals and TIPS becomes identical.[19]

Last, in the case of a TIPS liquidity event ($\delta_{\tau_\ell}^{(\ell)} > 0$), we assume that TIPS are terminated and provide a recovery payment of $e^{-\delta_{\tau_\ell}^{(\ell)}}$ per unit of inflated face value, i.e.

[19] To preserve the absence of arbitrage opportunities, we assume that the reference bond is not directly tradable by investors and is not part of the regular trading curve of sovereign nominals. One can thus view the formulation of Equation (Equation 3.19) as a pure reduced-form assumption where the recovery rate of any bond is given by $\mathcal{P}_t^{(n_r)}$, a quantity close to the price of a nominal bond of maturity n_r.

$e^{-\delta^{(\ell)}_{\tau_\ell}+\pi_{t+1}+\ldots+\pi_{\tau_\ell}}$. Thus, the magnitude of the $\delta^{(\ell)}_{\tau_\ell}$ jump represents the severity of the rebate of a TIPS sold on the secondary market.[20]

3.4.7 The term structure of sovereign Treasuries

Having defined recovery payments in case of default and liquidity events, we turn to pricing the term structures of sovereign bonds. The price of nominal bonds is given by:

$$\begin{aligned} B_t^{(n)} = \sum_{i=1}^{n} \mathbb{E}_t^{\mathbb{Q}} \left[\exp\left(-\sum_{j=0}^{i-1} r_{t+j}\right) \mathcal{P}^{(n_r)}_{t+i} \times \left(\mathbb{1}\left\{\sum_{j=0}^{i-1} \delta^{(c)}_{t+j} = 0\right\} - \mathbb{1}\left\{\sum_{j=0}^{i} \delta^{(c)}_{t+j} = 0\right\}\right)\right] \\ + \quad \mathbb{E}_t^{\mathbb{Q}} \left[\exp\left(-\sum_{j=0}^{n-1} r_{t+j}\right) \mathbb{1}\left\{\sum_{j=0}^{n} \delta^{(c)}_{t+j} = 0\right\}\right] . \quad (3.20) \end{aligned}$$

Equation (Equation 3.20) simply states that the price of the nominal bond is the sum of discounted recovery payments if default happens between $t+i-1$ and $t+i$ (first row), and the discounted principal if no default occurs during the lifespan of the bond (second row). An inflation-indexed bond is priced similarly, adding the possibility of liquidity risk. The

[20] While defining the recovery payment as a fraction of the price that would have prevailed in the absence of liquidity event (RMV) would be more realistic, it is not possible to obtain closed-form pricing formulas with that assumption in our framework. As noted by [108], differences between RMV and RFV assumptions tend to be small empirically, and this is unlikely to have a significant impact on our results.

price of the inflation-indexed bond is then given by:[21]

$$B_t^{*(n)} = \sum_{i=1}^{n} \mathbb{E}_t^{\mathbb{Q}} \left[\exp\left(-\sum_{j=0}^{i-1} r_{t+j} - \rho^* \pi_{t+j+1} \right) \mathcal{P}_{t+i}^{(n_r)} \times \left(\mathbb{1}\left\{ \sum_{j=0}^{i-1} \delta_{t+j}^{(c)} = 0 \right\} - \mathbb{1}\left\{ \sum_{j=0}^{i} \delta_{t+j}^{(c)} = 0 \right\} \right) \right]$$
$$+ \mathbb{E}_t^{\mathbb{Q}} \left[\exp\left(-\sum_{j=0}^{i-1} r_{t+j} - \pi_{t+j+1} \right) e^{-\delta_{t+i}^{(\ell)}} \times \mathbb{1}\left\{ \sum_{j=0}^{i} \delta_{t+j}^{(c)} = 0 \right\} \left(\mathbb{1}\left\{ \sum_{j=0}^{i-1} \delta_{t+j}^{(\ell)} = 0 \right\} - \mathbb{1}\left\{ \sum_{j=0}^{i} \delta_{t+j}^{(\ell)} = 0 \right\} \right) \right]$$
$$+ \mathbb{E}_t^{\mathbb{Q}} \left[\exp\left(-\sum_{j=0}^{n-1} r_{t+j} - \pi_{t+j+1} \right) \mathbb{1}\left\{ \sum_{j=0}^{n} \delta_{t+j}^{(c)} = 0 \right\} \mathbb{1}\left\{ \sum_{j=0}^{n} \delta_{t+j}^{(\ell)} = 0 \right\} \right]. \quad (3.21)$$

Equation (Equation 3.21) decomposes the price of a TIPS into the discounted recovery payment in case of default (first row), the discounted liquidity recovery in case of a liquidity event and no default event (second row), and the discounted inflated face value at maturity if no default and liquidity events happen (last row).

We show in Appendix subsection C.1.6 that our model provides closed-form pricing formulas for Equations (Equation 3.20-Equation 3.21), such that the price of a zero coupon nominal Treasury of residual maturity n is given by:

$$B_t^{(n)} = \lim_{\mathsf{u}\to+\infty} e^{\mathsf{A}_{n_r} - \kappa^{(r)\prime} w_t} \sum_{i=1}^{n} e^{-i\kappa_0^{(r)}} \left[\exp\left\{ \mathcal{A}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathsf{B}_{n_r} \right) + \mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathsf{B}_{n_r} \right)' w_t \right\} \right.$$
$$\left. - \exp\left\{ \mathcal{A}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathsf{B}_{n_r} - \mathsf{u}\mathbf{e}_c \right) + \mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathsf{B}_{n_r} - \mathsf{u}\mathbf{e}_c \right)' w_t \right\} \right]$$
$$+ \exp\left\{ -n\kappa_0^{(r)} + \mathcal{A}_n^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, -\mathsf{u}\mathbf{e}_c \right) + \left[\mathcal{B}_n^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, -\mathsf{u}\mathbf{e}_c \right) - \kappa^{(r)} \right]' w_t \right\}, \quad (3.22)$$

where the limit can be obtained numerically by putting a large scalar argument u, and for

[21] We leave aside the embedded option and the inflation lag for simplicity in these pricing formulas. First, note that the embedded inflation option would, if anything, raise the price of the TIPS, decrease its yield, thus play against a large ILS-BEI spread. Hence, by neglecting the deflation option, we underestimate the role of the other factors, if anything. In addition, notice that the value of this deflation floor would be the biggest during the financial crisis, where the ILS-BEI spread is the biggest. Our simplification is thus conservative. Second, while the inflation lag can matter for short-enough maturities (below 2y), it is unlikely to have a large impact for longer maturities since the 3-months lag represents a smaller proportion of the total maturity of the bond.

TIPS we have:

$$
\begin{aligned}
B_t^{*(n)} = \lim_{\mathsf{u}\to+\infty} \quad & e^{\mathsf{A}_{n_r}-\kappa^{(r)\prime}w_t} \sum_{i=1}^{n} e^{i\left(\rho^*\kappa_0^{(\pi)}-\kappa_0^{(r)}\right)} \Bigg[\exp\Big\{ \mathcal{A}_i^{\mathbb{Q}}\left(\rho^*\kappa^{(\pi)}-\kappa^{(r)}-\mathsf{u}\mathbf{e}_c,\, \rho^*\kappa^{(\pi)}+\mathsf{B}_{n_r}\right) \\
& + \quad \mathcal{B}_i^{\mathbb{Q}}\left(\rho^*\kappa^{(\pi)}-\kappa^{(r)}-\mathsf{u}\mathbf{e}_c,\, \rho^*\kappa^{(\pi)}+\mathsf{B}_{n_r}\right)' w_t \Big\} \\
- \exp\Big\{ & \mathcal{A}_i^{\mathbb{Q}}\left(\rho^*\kappa^{(\pi)}-\kappa^{(r)}-\mathsf{u}\mathbf{e}_c,\, \rho^*\kappa^{(\pi)}+\mathsf{B}_{n_r}-\mathsf{u}\mathbf{e}_c\right) + \mathcal{B}_i^{\mathbb{Q}}\left(\rho^*\kappa^{(\pi)}-\kappa^{(r)}-\mathsf{u}\mathbf{e}_c,\, \rho^*\kappa^{(\pi)}+\mathsf{B}_{n_r}-\mathsf{u}\mathbf{e}_c\right)' w_t \Big\} \Bigg] \\
& + e^{-\kappa^{(r)\prime}w_t} \sum_{i=1}^{n} e^{i\left(\kappa_0^{(\pi)}-\kappa_0^{(r)}\right)} \Bigg[\exp\Big\{ \mathcal{A}_i^{\mathbb{Q}}\left(\kappa^{(\pi)}-\kappa^{(r)}-\mathsf{u}\left(\mathbf{e}_c+\mathbf{e}_\ell\right),\, \kappa^{(\pi)}-\mathsf{u}\mathbf{e}_c-\mathbf{e}_\ell\right) \\
& + \quad \mathcal{B}_i^{\mathbb{Q}}\left(\kappa^{(\pi)}-\kappa^{(r)}-\mathsf{u}\left(\mathbf{e}_c+\mathbf{e}_\ell\right),\, \kappa^{(\pi)}-\mathsf{u}\mathbf{e}_c-\mathbf{e}_\ell\right)' w_t \Big\} \\
- \exp\Big\{ & \mathcal{A}_i^{\mathbb{Q}}\left(\kappa^{(\pi)}-\kappa^{(r)}-\mathsf{u}\left(\mathbf{e}_c+\mathbf{e}_\ell\right),\, \kappa^{(\pi)}-\mathsf{u}\left(\mathbf{e}_c+\mathbf{e}_\ell\right)\right) + \mathcal{B}_i^{\mathbb{Q}}\left(\kappa^{(\pi)}-\kappa^{(r)}-\mathsf{u}\left(\mathbf{e}_c+\mathbf{e}_\ell\right),\, \kappa^{(\pi)}-\mathsf{u}\left(\mathbf{e}_c+\mathbf{e}_\ell\right)\right)' w_t \Big\} \Bigg] \\
& + \exp\Big\{ n\left(\kappa_0^{(\pi)}-\kappa_0^{(r)}\right) + \mathcal{A}_n^{\mathbb{Q}}\left(\kappa^{(\pi)}-\kappa^{(r)}-\mathsf{u}\left(\mathbf{e}_c+\mathbf{e}_\ell\right),\, \kappa^{(\pi)}-\mathsf{u}\left(\mathbf{e}_c+\mathbf{e}_\ell\right)\right) \\
& + \quad \left[\mathcal{B}_n^{\mathbb{Q}}\left(\kappa^{(\pi)}-\kappa^{(r)}-\mathsf{u}\left(\mathbf{e}_c+\mathbf{e}_\ell\right),\, \kappa^{(\pi)}-\mathsf{u}\left(\mathbf{e}_c+\mathbf{e}_\ell\right)\right)-\kappa^{(r)}\right]' w_t \Big\}\,, \qquad (3.23)
\end{aligned}
$$

where $\mathbf{e}_\ell$ is such that $\delta_t^{(\ell)} = \mathbf{e}_\ell' w_t$. Despite the apparent complexity of these pricing formulas, note that they are weigthed sums of exponential-affine combinations of w_t and are hence computable easily through closed-form recursions. However, contrary to riskless term structures, the sovereign nominal and TIPS yields will not be affine functions of the factors, but rather non-linear combinations.

Last, we can easily obtain the BEI pricing formula by considering the log-difference of TIPS and nominal bond prices:

$$
\mathrm{BEI}_t^{(n)} = \frac{1}{n}\left(\log B_t^{*(n)} - \log B_t^{(n)}\right)\,. \qquad (3.24)
$$

3.4.8 The term structure of CDS

To identify sovereign credit risk, we consider the pricing of sovereign CDSs. Following our description of the CDS market in the previous sections, we assume that the protection seller delivers the nominal face value of any sovereign bond, irrespective of its nominal or inflation-protected nature, against the physical delivery of the cheapest-to-deliver bond.

Given our recovery assumptions, the cheapest-to-deliver in case of default is always the reference bond. Indeed, whatever the indexation honored by the sovereign government ρ^*, TIPS always deliver at least the same amount as nominal bonds in case of a credit event. Thus, the payment provided by the CDS is exactly equal to the loss given default of the nominal bonds, i.e. $1 - \mathcal{P}_{\tau_c}^{(n_r)}$. The present value of the protection sold is given by:

$$\mathrm{PS}_t^{(n)} = \sum_{i=1}^{n} \mathbb{E}_t^{\mathbb{Q}} \left[\exp\left(-\sum_{j=0}^{i-1} r_{t+j} \right) \left(1 - \mathcal{P}_{t+i}^{(n_r)} \right) \left(\mathbb{1}\left\{ \sum_{j=0}^{i-1} \delta_{t+j}^{(c)} = 0 \right\} - \mathbb{1}\left\{ \sum_{j=0}^{i} \delta_{t+j}^{(c)} = 0 \right\} \right) \right] .$$

We assume that a buyer of protection makes periodic payments from time t to maturity n to protect against any type of credit event. The cash flow payment at time $t+i$ conditional on no default is designated as $\mathcal{S}_t^{(n)}$. The present value of the stream of cash flows paid by the protection buyer is:

$$\mathrm{PB}_t^{(n)} = \mathcal{S}_t^{(n)} \sum_{i=1}^{n} \mathbb{E}_t^{\mathbb{Q}} \left[\exp\left(-\sum_{j=0}^{i-1} r_{t+j} \right) \mathbb{1}\left\{ \sum_{j=0}^{i} \delta_{t+j}^{(c)} = 0 \right\} \right]$$

No arbitrage pricing requires that the present value of the protection bought is equal to the present value of the protection sold. Equating both legs at inception, using the risk-neutral dynamics of subsection 3.4.2 and solving for the swap spread yields:

$$\mathcal{S}_t^{(n)} = \frac{B_t^{(n)} \left[\mathrm{RR}_{\tau_c} = 1 \right] - B_t^{(n)} \left[\mathrm{RR}_{\tau_c} = \mathcal{P}_{\tau_c}^{(n_r)} \right]}{\sum_{i=1}^{n} \exp\left\{ -i\kappa_0^{(r)} + \mathcal{A}_i^{\mathbb{Q}} \left(-\kappa^{(r)} - \mathbf{ue}_c, \ , -\mathbf{ue}_c \right) + \left[\mathcal{B}_i^{\mathbb{Q}} \left(-\kappa^{(r)} - \mathbf{ue}_c, \ , -\mathbf{ue}_c \right) - \kappa^{(r)} \right]' w_t \right\}} , \tag{3.25}$$

where the notation $B_t^{(n)} \left[\mathrm{RR}_{\tau_c} = 1 \right]$ represents the price of a nominal bond for a recovery rate of 100%, and $B_t^{(n)} \left[\mathrm{RR}_{\tau_c} = \mathcal{P}_{\tau_c}^{(n_r)} \right]$ is the exact pricing formula presented in Equation (Equation 3.22) (see Appendix subsection C.1.7).

3.5 Data and Estimation

3.5.1 Data and identification

Let us first describe our empirical targets. All of our data is selected at the monthly frequency from November 2004 to October 2015, for data availability reasons. We select the 6m overnight-indexed swap (OIS) to guide our estimation for short-term riskless nominal yields, and select inflation-linked swap yields at maturities 1y, 2y, 3y, 5y, 7y, and 10y. Risky bonds are represented by GSW nominal Treasury yields at maturities 1y, 2y, 3y, 5y, 7y, and 10y, and by GSW breakeven inflation rates based on Treasuries of maturities 2y, 3y, 5y, 7y, and 10y. Instead of fitting the breakevens, we fit the ILS-BEI spreads, our main object of interest. We identify credit risk with the term structure of U.S. sovereign CDSs of maturities 2y, 3y, 5y, 7y, and 10y. Because all CDSs are virtually constant in the beginning of our sample, we consider their observations before 2008 as missing data. The liquidity intensity is identified by assuming that it relates linearly to the series of TIPS fitting errors obtained from a Nelson-Siegel-Svensson model.[22] We add monthly inflation data computed as the log-change of the CPI-U index provided by the Bureau of Labor Statistics (BLS). Lastly, we impose that $\delta_t = \mathbf{0}$ in the estimation procedure, thus δ_t are also part of the observable variables. We end up gathering 27 observable variables for each date denoted by $\mathcal{Y}_t \in \mathbb{R}^{27}$ that are all measured with error except inflation.

Using the state dynamics of Equation (Equation 3.10), the model can be expressed in state-space form where the measurement equations are given by:

$$\mathcal{Y}_t = \mathsf{F}\left(w_t,\, \vartheta^{\mathbb{Q}}\right) + \eta_t\,, \tag{3.26}$$

where η_t is a vector of i.i.d. Gaussian measurement errors with mean zero, $\mathsf{F}\left(w_t,\, \vartheta^{\mathbb{Q}}\right)$ is a non-linear function of the state, and $\vartheta^{\mathbb{Q}}$ represents the set of risk-neutral parameters driving the pricing equations. Since some of the pricing equations are non-linear, we estimate the

[22] We are grateful to Richard Crump for providing the data.

model with the Extended Kalman Filter (EKF). The closed-form gradients of the pricing equations used for filtering are detailed in Appendix subsection C.1.8.

In our estimation, we consider $N_x = 3$, $N_{y_c} = 2$ and $N_{y_\ell} = 1$. Our latent factors are identified through the following constraints. First, we impose that $\mu = \mathbf{0}$, Φ is lower-triangular, and $\Sigma = I_{N_x}$ such that x_t cannot be rotated. Second, we fix β_y as lower-triangular such that credit factors Granger-cause liquidity factors, consistent with the intuition. Diagonals of both Φ and $\text{diag}(\mathsf{c})\beta$ are in the unit circle to ensure stationarity. For the scaling of y_t, we set $\mathsf{c}_y^{\mathbb{Q}} = \mathbf{1}$. For parsimony, we impose that the covariance matrix of measurement errors to be diagonal, and each block of observables have a different standard deviation parameter. We set the standard deviation of the liquidity proxy measurement errors to a fifth of its in-sample standard deviation, as it provides a reasonable fit of the proxy. Last, some parameters are technically identified but the log-likelihood is nearly flat close to their estimates. A first round of estimation shows that this is the case for c_δ for the credit-event variable, which we set to 0.6 (see [70]), and for the indexation parameter ρ^*. We set it to 0 in the estimation, noting that switching it to 1 barely changes the remaining estimates after estimation. We end up with a total of 52 parameters.

3.5.2 Parameter estimates

The estimates obtained from our maximum likelihood procedure are reported in Table 3.10. All parameters are significant at the 5% level. As expected, all processes are extremely persistent under both the physical and the risk-neutral measure. It is worth analyzing the parameters of the inflation equation. First, we obtain a negative correlation between the credit-event intensity factors $y_t^{(c)}$ and inflation, with parameters $\kappa_y^{(\pi)} = (-0.1915, -0.0022)'$ annualized. Therefore, inflation tends to go down when the probability of a sovereign default goes up, consistent with the increased risk of deflation happening during the financial crisis. Second, our model estimates favor the existence of hyperinflation upon default, with a feedback of the credit-event variable on inflation at $\kappa_\delta^{(\pi)} = 0.3138$.

Economically, this estimate translates into an average monthly inflation jump of 18.8 percentage points, about 40 times its standard deviation during the sample.

Table 3.10: **Term structure model parameter Estimates**

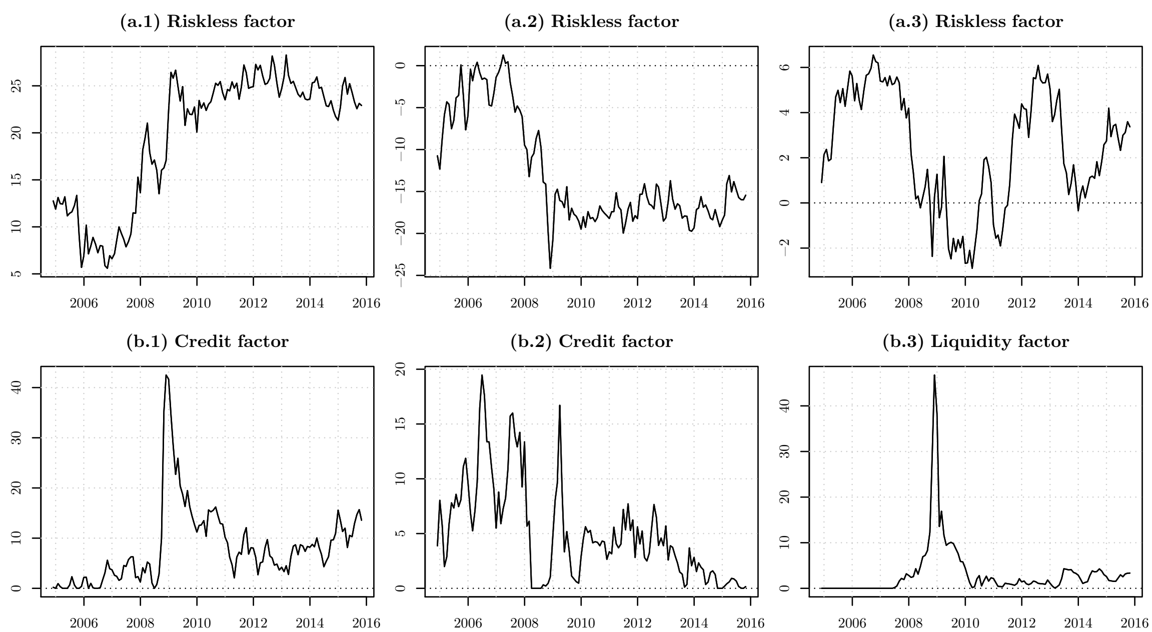
Estimation is performed by extended Kalman filter-based maximum likelihood. For numerical stability, we impose that the time series of δ_t are fitted in the filter but treat them as unobservables as far as the likelihood is concerned. This avoids the filter to favor parameter estimates where the pricing of observables is down-weighted with respect to the dynamics of $\delta_t = 0$. Standard errors are of estimation are computed with outer-product approximation and are reported in brackets. When the parameter has been calibrated or the estimates hit the bound, we report '–' instead of the standard errors. Although not introduced in the main text, $\kappa_0^{(\ell)}$ and $\kappa^{(\ell)}$ are the parameters governing the liquidity proxy equation, such that the proxy is equal to $\kappa_0^{(\ell)} + \kappa^{(\ell)\prime}\, w_t$.

	μ	Φ				$1200 \cdot \kappa_x^{(r)}$	$1200 \cdot \kappa_x^{(\pi)}$	$\kappa_x^{(\ell)}$	$\mu^{\mathbb{Q}}$	$\Phi^{\mathbb{Q}}$		
x_t	0	0.99999	0	0		0.0950	1.2094	0	−0.1854	0.8151	−0.2330	0.2328
	–	–	–	–		[0.0451]	[0.2811]	–	[0.0396]	[0.0478]	[0.0616]	[0.0385]
	0	−0.00011	0.9991	0		0.4586	1.6251	0	−0.0894	−0.3711	0.5033	0.3461
	–	[0.00005]	[0.0018]	–		[0.0736]	[0.2193]	–	[0.0796]	[0.1020]	[0.0462]	[0.0732]
	0	0.1548	0.2086	0.8878		−0.1809	−1.3238	0	0.0039	−0.0215	−0.0270	1.0071
	–	[0.0374]	[0.0600]	[0.0549]		[0.0580]	[0.2041]	–	[0.00002]	[0.0077]	[0.0064]	[0.0137]
	ν	β			c_y	$\kappa_y^{(r)}$	$1200 \cdot \kappa_y^{(\pi)}$	$\kappa_y^{(\ell)}$	θ_y	$\beta^{\mathbb{Q}}$		
y_t	0.0904	0.9490	0	0	0.9912	0	−0.1915	0	0.0089	0.9574	0	0
	[0.0230]	[0.00001]	–	–	[0.0019]	–	[0.0058]	–	[0.0019]	[0.0018]	–	–
	0.0747	0.0031	0.99999	0	0.9921	0	−0.0022	0	0.0080	0.0032	1.0080	0
	[0.0119]	[0.0015]	–	–	[0.0001]	–	[0.0004]	–	[0.0001]	[0.0015]	[0.0001]	–
	0.0279	0.00007	0.0054	0.9776	0.9750	0	0	0.7226	0.0257	0.0001	0.0055	1.0027
	[0.0058]	[0.000005]	$[4 \cdot 10^{-8}]$	[0.0139]	[0.0125]	–	–	[0.0424]	[0.0131]	[0.000005]	[0.0021]	[0.0048]
		$1200 \cdot \beta_\lambda$			c_δ	$\kappa_\delta^{(r)}$	$\kappa_\delta^{(\pi)}$	$\kappa_\delta^{(\ell)}$				
$\delta_t^{(c)}$		0.0060	0.0407	0	0.6	0	0.3138	0				
		[0.0011]	[0.0066]	–	–	–	[0.0308]	–				
$\delta_t^{(\ell)}$		0	0	0.2265	0.3330	0	0	0				
		–	–	[0.0227]	[0.0366]	–	–	–				
	σ_{ois}	σ_{ILS}	σ_{nom}	$\sigma_{\mathrm{ILS-BEI}}$	σ_{CDS}	$\kappa_0^{(r)}$	$\kappa_0^{(\pi)}$	$\kappa_0^{(\ell)}$				
	0.4621	0.1376	0.1149	4.0083	0.1025	0.0048	0.0033	2.5967				
	[0.0628]	[0.0041]	[0.0037]	[0.1386]	[0.0034]	[0.0020]	[0.0004]	[0.1529]				

The six latent factors, x_t and y_t, filtered by our model are plotted in Figure 3.3. The first three factors x_t are presented on panel (a) and control the term structure of discount rates as well as part of the inflation dynamics. Panel (b) presents the three components of the factors y_t, controlling the default and liquidity-event probabilities. In panels (b.1) and (b.2), we see that the credit factors allow us to perfectly track CDS spreads, reproducing the large spike observed during the financial crisis and staying elevated afterwards. In contrast, the liquidity factor experiences one large spike in 2008 and dies out quickly afterwards.

Figure 3.3: Filtered Factors

Factors are estimated by extended Kalman filter. Data range from 2004 to 2015. Panels (a.1) to (a.3) present the three components of x_t while panels (b.1) to (b.3) present the three components of y_t. (b.1) and (b.2) correspond to the credit factors $y_t^{(c)}$ whereas (b.3) corresponds to $y_t^{(\ell)}$.



3.5.3 Model performance

We now turn to the fitting properties of the model. We present RMSEs and R-squared measures in Table 3.11. The model does a tremendous job in capturing the bulk of fluctuations of the four different term structures and the monthly inflation rate with only 6 factors. All RMSEs, besides OIS, are between 2bps and 16.5bps, with ranges of [10.5bps-16.5bps] for the ILS term structure, [5.4bps-11.3bps] for the nominal term structure, [7.6bps-14bps] for the ILS-BEI term structure, and [2.6bps-4.7bps] for the CDS term structure. As a result, many R-squared are above 98%, and most of them are well above 80%. By construction, the R-squared on inflation is 1, since we imposed that inflation is measured without errors. Note that only the OIS shows a slightly worse performance, since we did not impose consistency of the model with the ZLB, a crucial feature for reproducing the short-end of the curve.

Table 3.11: **Observable variables Root mean squared error and R-squared**

All RMSEs are in basis points while R^2 measures are in natural units. 'ILS' stands for inflation-linked swaps, 'Nominal' is the corresponding Treasury curve, 'ILS-BEI' is the spread between inflation-linked swaps and equivalent maturity Treasury breakevens, 'CDS' correspond to the U.S. sovereign CDS spreads, 'OIS' is the 6m overnight indexed swap rate, π_t is the monthly annualized inflation rate and 'Liq' is the liquidity proxy defined as the errors from a Nelson-Siegel-Svensson model applied on the TIPS individual bonds.

		1y	2y	3y	5y	7y	10y
ILS	RMSE (bps)	16.45	10.96	10.61	11.3	13.19	14.35
	R^2	(0.983)	(0.986)	(0.98)	(0.957)	(0.907)	(0.811)
Nominal	RMSE (bps)	9.64	7	10.08	8.83	5.4	11.32
	R^2	(0.997)	(0.998)	(0.996)	(0.996)	(0.998)	(0.988)
ILS-BEI	RMSE (bps)		14.04	11.03	10.53	8.1	7.6
	R^2		(0.833)	(0.864)	(0.843)	(0.829)	(0.718)
CDS	RMSE (bps)		4.71	3.01	3.47	2.63	3.93
	R^2		(0.833)	(0.939)	(0.94)	(0.964)	(0.913)
		OIS	π_t	Liq			
	RMSE (bps)	43	4.53	1.8			
	R^2	(0.953)	(1)	(0.867)			

We also present the time series of the fitted values produced by the model for the OIS yield, the ILS term structure, the nominal Treasury term structure, the ILS-BEI spreads, and the CDS term structure on Figure 3.4, Figure 3.5, Figure 3.6, Figure 3.7, and Figure 3.8, respectively. Fitted values are virtually indistinguishable from the observed data for most of the observables, confirming the outstanding fitting performance of our term structure framework. We are thus confident that our model is successful in identifying the different pricing components, namely credit and liquidity, contained in the different observable variables that we used as inputs.

Figure 3.4: 6m OIS, inflation and liquidity proxy fitted values

The model is estimated with extended Kalman filter. Data range from 2004 to 2015. The black solid line presents the observation data used as input for estimation. The grey dashed line presents the fitted values produced through the filtered factors presented on Figure Figure 3.3.

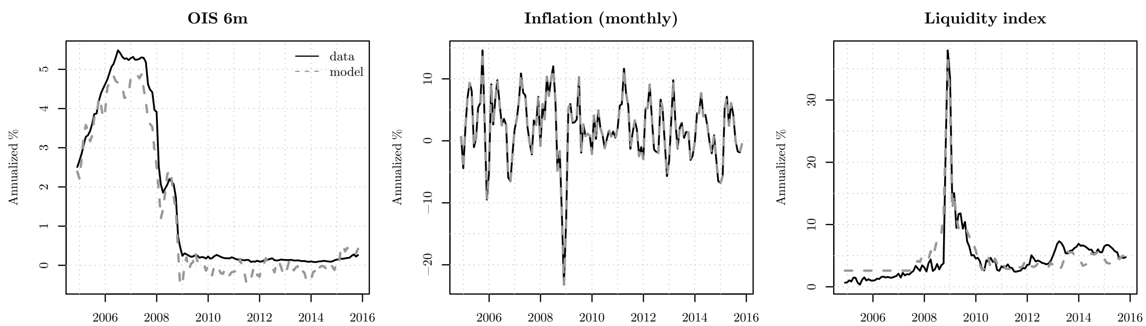


Figure 3.5: Inflation-linked swaps fitted values

The model is estimated with extended Kalman filter. Data range from 2004 to 2015. The black solid line presents the observation data used as input for estimation. The grey dashed line presents the fitted values produced through the filtered factors presented on Figure 3.3.

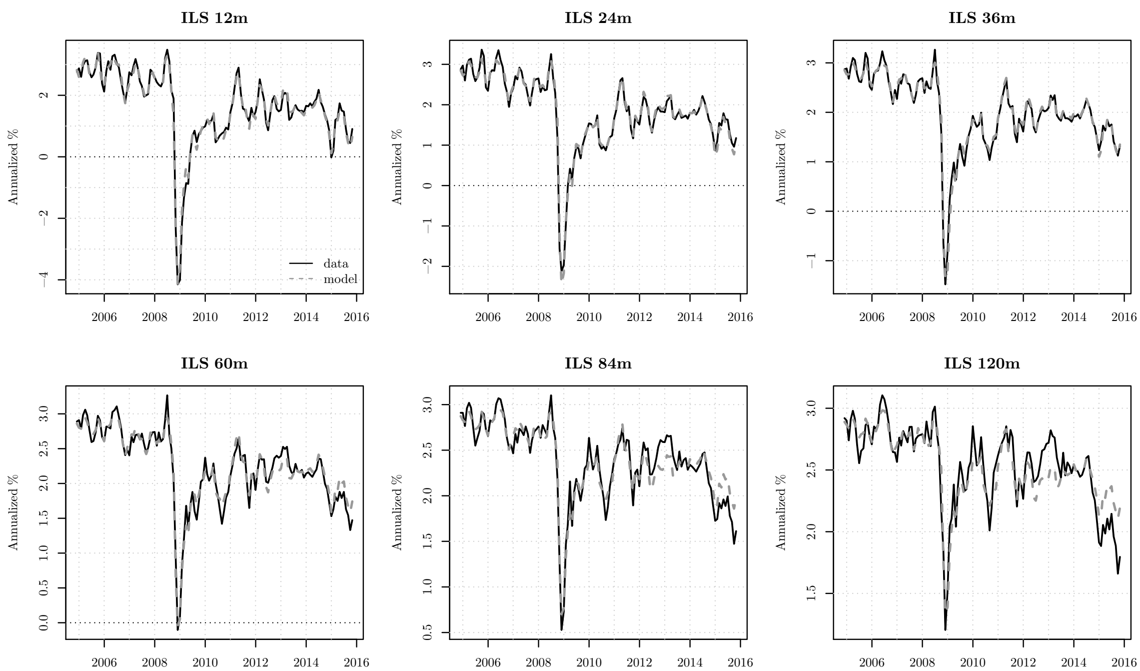


Figure 3.6: Nominal Treasuries fitted values

The model is estimated with extended Kalman filter. Data range from 2004 to 2015. The black solid line presents the observation data used as input for estimation. The grey dashed line presents the fitted values produced through the filtered factors presented on Figure 3.3.

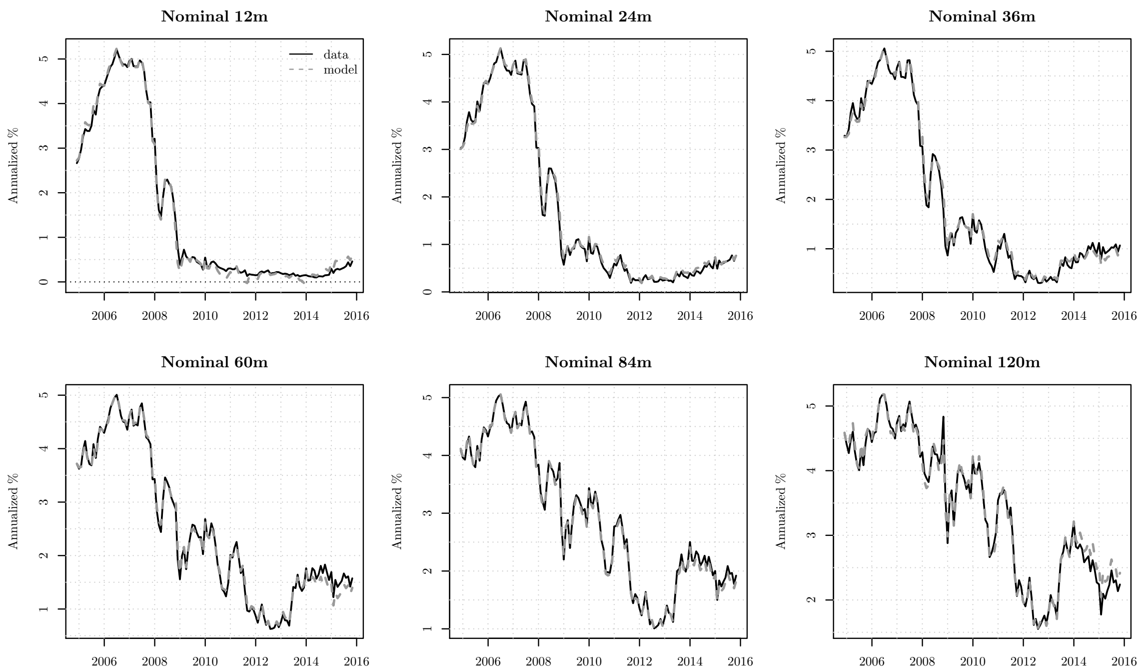


Figure 3.7: ILS-BEI spreads fitted values

The model is estimated with extended Kalman filter. Data range from 2004 to 2015. The black solid line presents the observation data used as input for estimation. The grey dashed line presents the fitted values produced through the filtered factors presented on Figure 3.3.

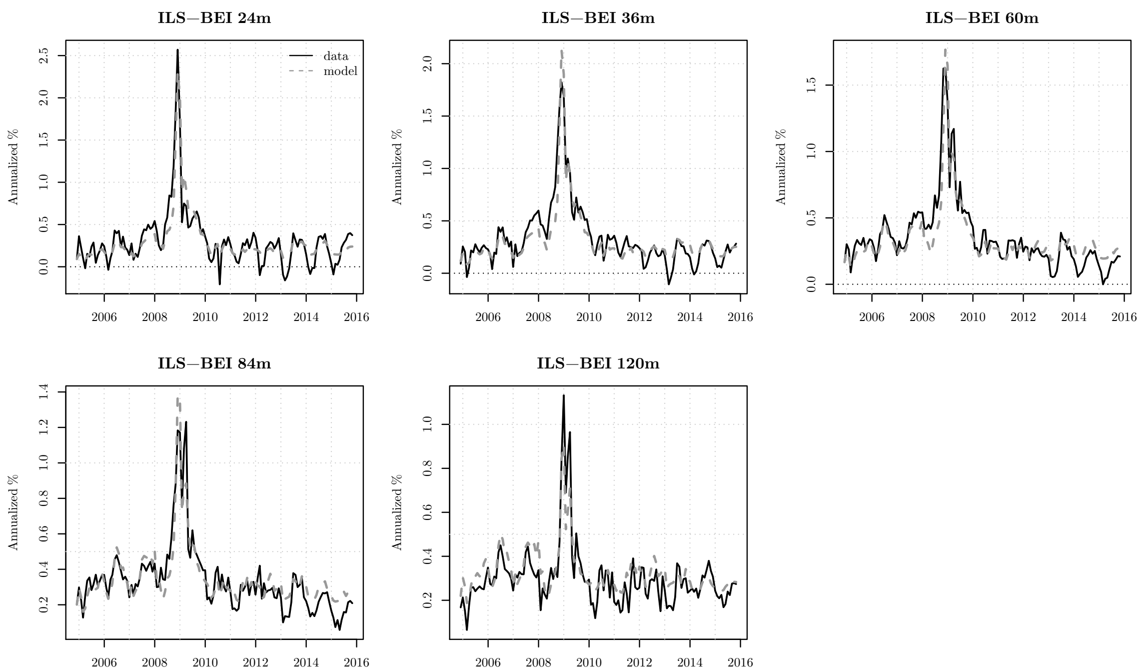
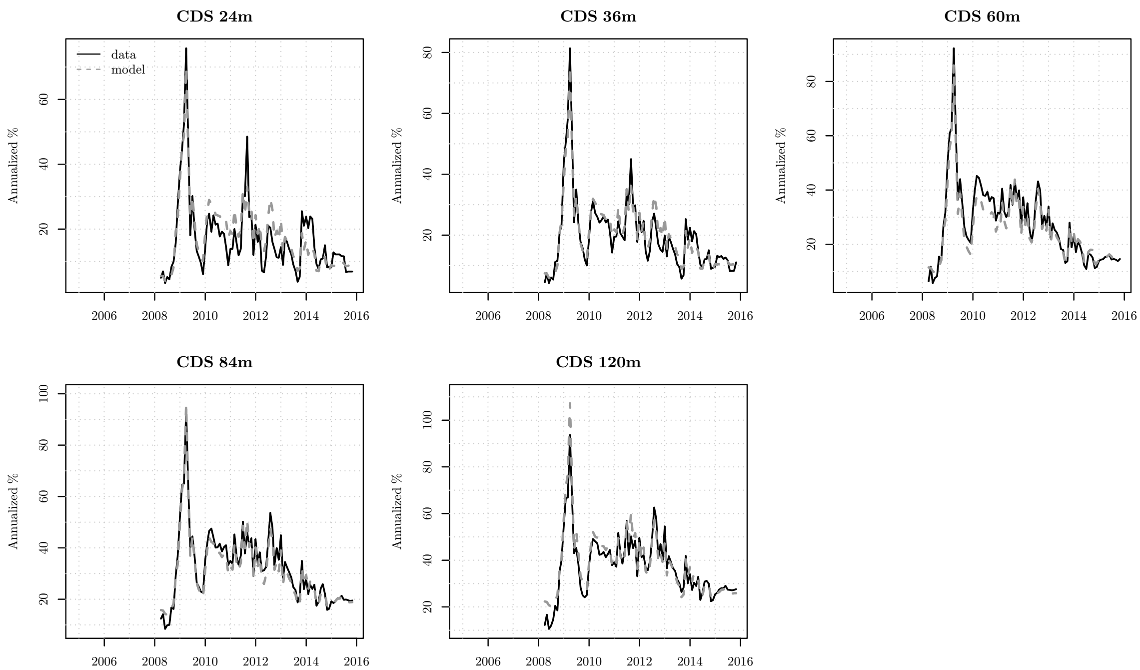


Figure 3.8: U.S. sovereign CDS spreads fitted values

The model is estimated with extended Kalman filter. Data range from 2004 to 2015. The black solid line presents the observation data used as input for estimation. The grey dashed line presents the fitted values produced through the filtered factors presented on Figure 3.3.



3.5.4 Decomposition of ILS-BEI Spreads

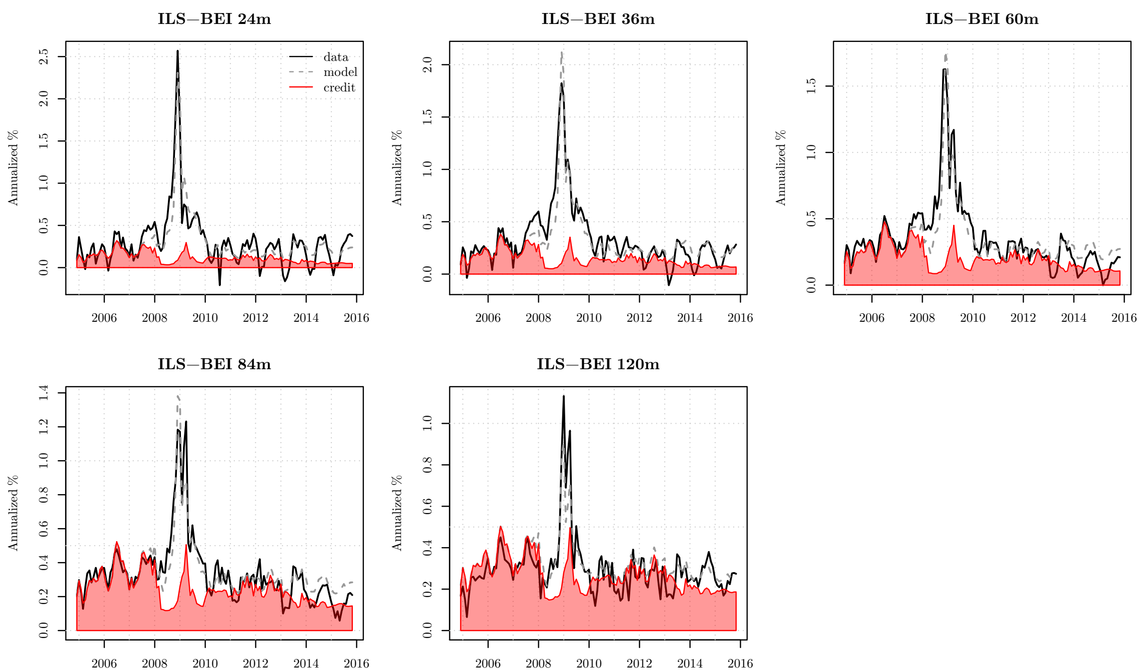
To understand the relative importance of default risk in driving a wedge between ILS and BEI, we fit the term structure of ILS-BEI spreads by employing only the credit risk factors $y_t^{(c)}$. The results are plotted Figure 3.9.

Three observations can be discerned from Figure 3.9. First, the credit component of the ILS-BEI spread contributes nearly completely to the overall fit of the curves prior to 2008. This is because we have considered the CDS term structure as missing data before the financial crisis, as seen in Figure Figure 3.8. As a result, the filter interprets our credit factors as essentially unconstrained by the CDSs, and it uses the flexibility of these factors to concentrate on fitting the ILS-BEI spreads. Second, in the middle of the crisis around September of 2008, the peak of the ILS-BEI spread is mostly driven by the liqudity factor.

This is not surprising either since the peaks of the liquidity proxy and the peak observed on the ILS-BEI spreads coincide. In contrast, the credit component remains low until it peaks in 2009. Third, the credit component of the ILS-BEI spread is the dominant factor in capturing the variability of the ILS-BEI curves in the data in the post-crisis period. The credit component represents between 20bps and 40bps of the ILS-BEI spreads in the post crisis period, depending on the time and maturity.

Figure 3.9: Credit component in ILS-BEI spreads

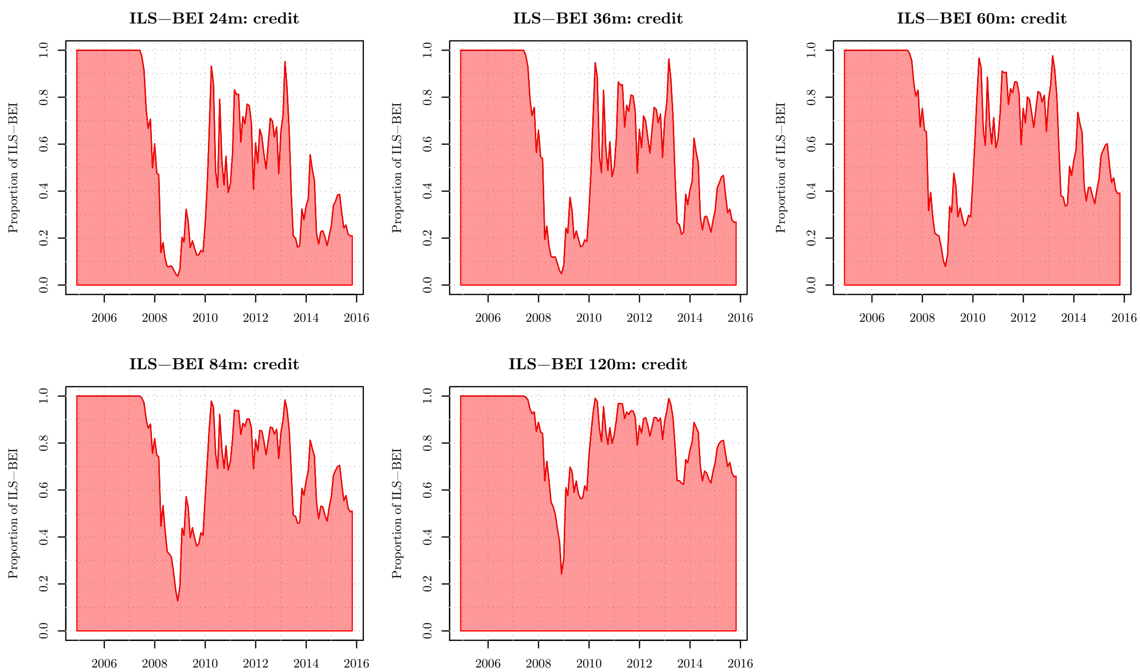
The model is estimated with extended Kalman filter. Data range from 2004 to 2015. The black solid line presents the observation data used as input for estimation. The grey dashed line presents the fitted values produced through the filtered factors presented on Figure 3.3. The red component represents the ILS-BEI spreads that would be obtained would the liquidity intensity (or, equivalently, $y_t^{(\ell)}$ be 0 throughout the sample.



The credit component does not show strong term structure effects, its absolute magnitude being roughly constant with respect to maturity. However, since the ILS-BEI mean and volatility compresses with maturity, the relative importance of the credit component grows with maturity. We plot the importance of credit risk as a ratio of the ILS-BEI spreads on Figure 3.10. We see that the proportion explained by credit risk indeed increases with maturity, especially during the 2010-2014 period where it represent about 60% of the 2y spread against about 90% of the 10y spread. Although credit risk goes down at the end of our sample, it remains an important driver of the ILS-BEI spreads.

Figure 3.10: Credit component in ILS-BEI spreads

The model is estimated with extended Kalman filter. Data range from 2004 to 2015. The red component represents the ILS-BEI spreads that would be obtained would the liquidity intensity (or, equivalently, $y_t^{(\ell)}$ be 0 throughout the sample, as a proportion of the fitted values presented on Figure 3.7 as a grey dashed line.



Our asset pricing model validates the results of our panel regressions in subsection 3.3.2. In particular, over the full sample between 2008 and 2015, the U.S. CDS spread driven by the credit factors has positive and significant explanatory power of the ILS-BEI spreads after controlling for liquidity. Moreover, contrasting Column (7) in Table 3.5 and Table 3.6, we see that the explanatory power of the credit component (proxied by the CDS spread) is statistically weaker (t-statistic of 2.16) during the crisis period and much stronger (t-statistic of 4.46) in the post-crisis period. Whereas the opposite is true for the liquidity factor (proxied by the OTR Difference) with t-statistic of 2.66 in Table Table 3.5 and t-statistic of 0.57 in Table 3.6. This is consistent with the decomposition of the fitted ILS-BEI curves shown in Figures Figure 3.9 and Figure 3.10.

3.5.5 Credit risk premium and mispricing

Our estimated term structure model also allows us to perform a risk-premium decomposition of the ILS-BEI. We thus ask how much of the credit component and the total risk premium charged on ILS-BEI is the result of investors charging a differential credit risk premium to nominal bonds and TIPS. To obtain risk premia components, we recompute counterfactual ILS-BEI spreads under the expectation hypothesis (i.e. risk-neutral parameters are set to the corresponding physical parameter estimates), and subtract them from the observed ILS-BEI. This provides us the total risk premia on the spreads. Similarly, we compute the counterfactual expectation hypothesis spreads setting the liquidity factor to zero, and subtract them from the credit components to obtain credit risk premia.

Figure 3.11: Total risk premia and credit risk premia in ILS-BEI spreads

The model is estimated with extended Kalman filter. Data range from 2004 to 2015. The green and blue components represent the total and credit risk premia, respectively, contained in ILS-BEI spreads. Total risk premia are obtained replacing the risk-neutral parameters by the physical ones and recomputing the ILS-BEI spreads given the estimated factors. The same procedure is applied for the credit premia, imposing the liquidity factor $y_t^{(\ell)}$ is equal to zero.

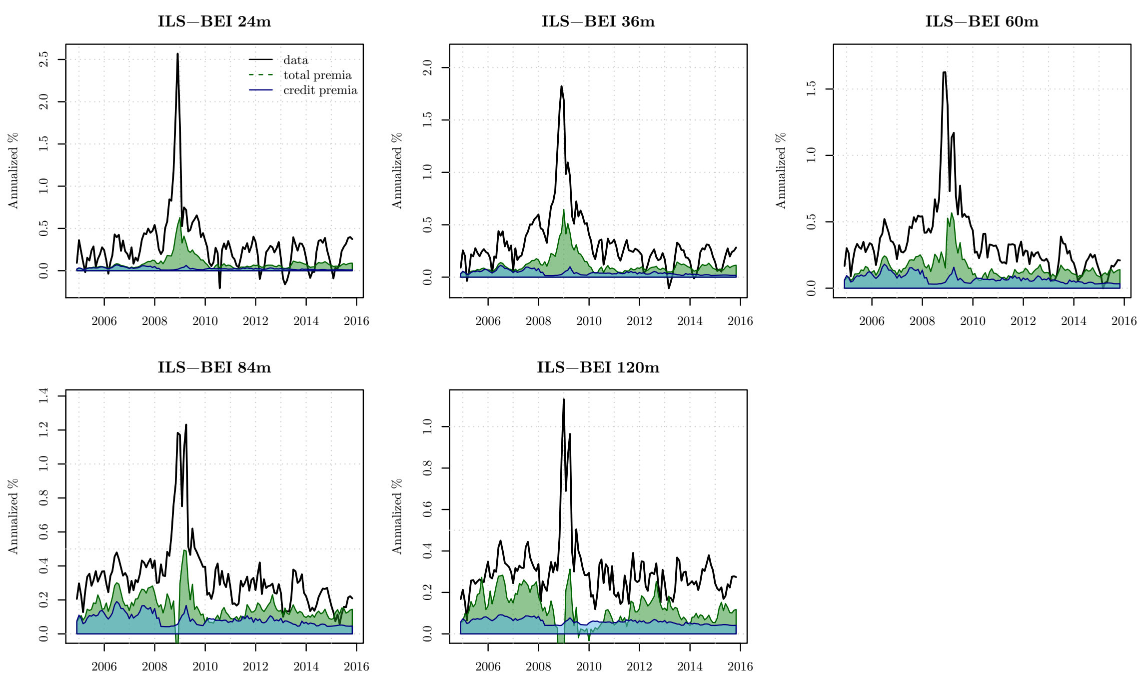


Figure 3.12: Credit component and credit risk premia in ILS-BEI spreads

The model is estimated with extended Kalman filter. Data range from 2004 to 2015. The red and blue components represent the credit component and risk premia, respectively, contained in ILS-BEI spreads. The credit component is computed by setting the liquidity factor $y_t^{(\ell)}$ to zero. Credit risk premia are obtained replacing the risk-neutral parameters by the physical ones and recomputing the ILS-BEI spreads given the estimated factors, imposing the liquidity factor $y_t^{(\ell)}$ is equal to zero.

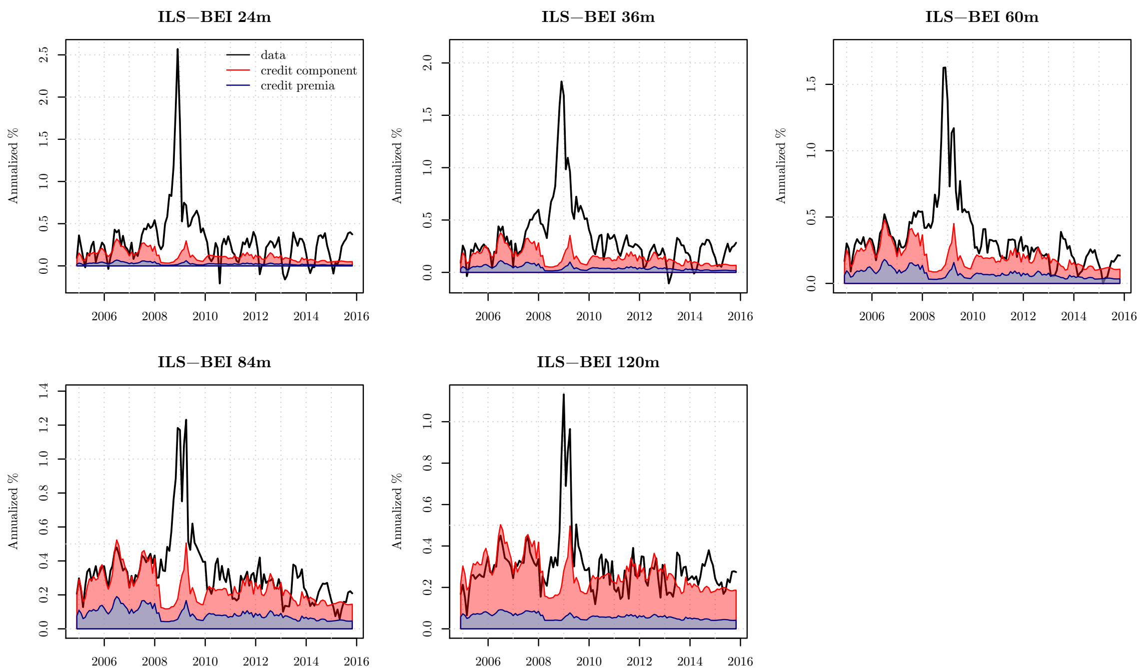


Figure 3.11 and Figure 3.12 present the credit risk premia contained in ILS-BEI spreads along with the total risk premia and the credit component, respectively. Two main conclusions emerge from the figures. First, credit risk premia represent about a quarter to a third of both the total premia and the credit component, between 10bps and 20bps. Second, the credit premia is highly correlated with the credit component contained in ILS-BEI spreads so they both follow the same factor structure. This shows that investors risk premia tend to grow hand in hand with the differential exposure of nominal Treasuries and TIPS. This seems to be consistent with the outstanding share of TIPS being roughly constant at 10% of the total outstanding U.S. debt.

3.6 Conclusion

In this paper, we explore the relative pricing of nominal and real U.S. sovereign securities in the presence of credit risk. We argue that while most of the previous studies attribute the mispricing of TIPS to liquidity factors or slow moving capital, credit risk can also represent a significant driver of deviations oftentimes interpreted as violations of no-arbitrage. Our study shows that in the presence of credit risk, the spreads between inflation-linked swaps and breakeven inflation rates reflect differences in the propensity of the sovereign to reimburse nominal and real bonds in case of default. We hypothesize this result is driven by a difference in recovery rates. Our empirical approach shows U.S. CDS spreads are positively correlated with first differences in ILS-BEI spreads after the financial crisis, while controlling for liquidity and potential alternative explanations. We then conduct a more formal empirical analysis through an intensity-based affine asset pricing model. We show that credit risk factors extracted from the CDS are able to explain most of the ILS-BEI yield curve after the financial crisis. Our model estimates confirm the existence of a lower recovery rate for TIPS than for nominal bonds by about 8 percentage points.

Appendices

APPENDIX A

PENSION RISK TRANSFER AND FIRM LEVERAGE: THE CASH FLOW VOLATILITY CHANNEL

Table A.1: **Risk Transfer Debt Effects - Exclude GM**

Table A.1 presents results from a regression of changes in several measures of firm leverage on event-year indicators and changes in a series of financial control variables. I exclude General Motors in all regressions. in All dependent variables are scaled by consolidated assets. The dependent variable in column (1), ΔPen Debt, is the change in pension obligations. ΔLT Debt, column (2) is the change in long-term financial debt. The dependent variable in column (3), Δ Tot Debt, represents changes in the sum of pension obligations, long-term, and short-term debt. $Pen\ Deficit$ represents the underfunded status of the pension plan (liabilities less assets). $CFP\ Vol\ Ratio$ is the cash flow volatility measure described in equation (1). MTB is the log of market value of equity, less book value of equity, plus balance sheet assets divided by balance sheet assets. $Total\ Assets$ is the log of balance sheet assets. ROA is defined as net income divided by balance sheet assets. $Collateral$ is the ratio of net property plant and equipment to balance sheet assets. $LumpsumYear$ is a indicator variable equal to one for any firm-year where a sponsor offered a lumpsum buyout. Year fixed-effects are included in each specification. Standard errors are clustered at the firm-level.

	(1) ΔPen Debt / Cons Asset	(2) ΔLT Debt / Cons Asset	(3) Δ Tot Debt / Cons Asset
$Year_{t-3+}$	0.001	0.000	0.001
	(1.04)	(0.01)	(0.52)
$Year_{t-2}$	-0.003	0.005	-0.003
	(-1.36)	(0.77)	(-0.53)
$Year_0$	-0.033***	0.004	-0.024***
	(-6.97)	(0.65)	(-3.91)
$Year_{t+1}$	-0.005*	0.022***	0.017**
	(-1.75)	(2.87)	(2.19)
$Year_{t+2}$	-0.002	-0.017	-0.003
	(-0.77)	(-1.01)	(-0.49)
$Year_{t+3+}$	-0.002	0.004	-0.009
	(-0.95)	(0.68)	(-0.77)
$\Delta Pen\ Deficit$	1.179***	-0.186**	1.048***
	(13.11)	(-2.02)	(8.60)
$\Delta CFP\ Vol\ Ratio$	0.002**	-0.015***	-0.014***
	(2.51)	(-3.30)	(-3.39)
ΔMTB	0.009***	-0.028***	-0.021**
	(4.74)	(-3.31)	(-2.10)
$\Delta BS\ Assets$	-0.032***	0.045**	0.025
	(-7.47)	(2.29)	(1.35)
ΔROA	-0.006	-0.145***	-0.190***
	(-1.26)	(-6.20)	(-4.80)
$\Delta Collateral$	0.041***	0.044	0.113
	(4.45)	(0.59)	(1.43)
$LumpsumYear$	-0.013***	0.008	-0.005
	(-5.85)	(1.18)	(-0.83)
Constant	0.002***	0.006***	0.010***
	(6.84)	(4.87)	(7.59)
Year FE	Yes	Yes	Yes
R-squared	0.612	0.059	0.156
Observations	7343	7343	7343

t statistics in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A.2: **Cross-Section of Financial Constraints (ZSCORE)**

Table A.2 presents results from a regression of changes in several measures of firm leverage on event-year indicators and changes in a series of financial control variables. Columns (1)-(3) consist of financially unconstrained firms while columns (4)-(6) consist of financially constrained firms based on the median of the zscore (3.3× Pre-Tax Income + Sales + 1.4×Retained earnings + 1.2×(current assets – current liabilities)/balance sheet assets. All dependent variables are scaled by consolidated assets. The dependent variables ΔPen Debt, ΔLT Debt, Δ Tot Debt are the changes in pension obligations, long-term financial debt, and total debt (sum of pension obligations, long-term, and short-term debt) respectively. $Pen\ Deficit$ represents the underfunded status of the pension plan (liabilities less assets). MTB is the log of market value of equity, less book value of equity, plus balance sheet assets divided by balance sheet assets. $Total\ Assets$ is the log of balance sheet assets. ROA is defined as net income divided by balance sheet assets. $Collateral$ is the ratio of net property plant and equipment to balance sheet assets. $LumpsumYear$ is a indicator variable equal to one for any firm-year where a sponsor offered a lumpsum buyout. Year fixed-effects are included in each specification. Standard errors are clustered at the firm-level.

	(1) ΔPen Debt/Cons At	(2) ΔLT Debt/Cons At	(3) Δ Tot Debt /Cons At	(4) ΔPen Debt/Cons At	(5) ΔLT Debt/Cons At	(6) Δ Tot Debt/Cons At
$Year_{t-3+}$	0.001	-0.000	0.002	0.004	0.002	0.003
	(1.05)	(-0.16)	(0.69)	(1.13)	(0.31)	(0.37)
$Year_{t-2}$	0.002	-0.006	-0.008	-0.009**	0.018	0.001
	(0.90)	(-0.96)	(-1.39)	(-2.22)	(1.52)	(0.08)
$Year_0$	-0.038***	0.001	-0.031***	-0.023***	0.003	-0.019**
	(-5.58)	(0.17)	(-3.81)	(-5.03)	(0.31)	(-2.10)
$Year_{t+1}$	-0.006***	0.029**	0.023*	-0.003	0.010	0.009
	(-2.80)	(2.56)	(1.94)	(-0.67)	(1.13)	(1.00)
$Year_{t+2}$	0.003	-0.013	-0.010	-0.007	-0.026	-0.004
	(0.68)	(-1.64)	(-1.18)	(-1.50)	(-0.82)	(-0.42)
$Year_{t+3+}$	-0.003	0.019***	0.017***	-0.003	-0.007	-0.027
	(-0.65)	(3.13)	(3.05)	(-0.90)	(-0.93)	(-1.48)
$\Delta Pen\ Deficit$	0.914***	-0.069	0.723***	1.332***	-0.227	1.265***
	(24.83)	(-0.92)	(9.67)	(12.93)	(-1.53)	(8.94)
ΔMTB	0.006***	-0.024**	-0.012	0.010***	-0.027**	-0.026*
	(3.01)	(-2.23)	(-1.15)	(3.51)	(-2.39)	(-1.85)
$\Delta BS\ Assets$	-0.059***	0.077***	0.071***	-0.025***	0.050**	0.022
	(-10.39)	(3.17)	(3.02)	(-4.90)	(2.53)	(1.20)
ΔROA	0.006	-0.144***	-0.267***	-0.012**	-0.136***	-0.156***
	(0.79)	(-2.83)	(-5.98)	(-2.33)	(-5.37)	(-3.40)
$\Delta Collateral$	0.037***	0.225***	0.291***	0.037***	-0.032	0.029
	(2.68)	(3.41)	(4.72)	(3.23)	(-0.31)	(0.27)
$LumpsumYear$	-0.012***	0.007	-0.003	-0.014***	0.010	-0.007
	(-4.38)	(1.44)	(-0.56)	(-4.38)	(0.67)	(-0.47)
$Constant$	0.003***	0.002	0.002	0.002***	0.008***	0.015***
	(7.17)	(1.16)	(1.30)	(3.97)	(4.38)	(7.64)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.594	0.096	0.230	0.648	0.056	0.145
Observations	3692	3692	3692	3423	3423	3423

t statistics in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A.3: **Cross-Section of Financial Constraints (Credit Rating)**

Table A.3 presents results from a regression of changes in several measures of firm leverage on event-year indicators and changes in a series of financial control variables. Columns (1)-(3) consist of investment grade firms while columns (4)-(6) consist of high yield. Firms which do no have an S&P rating are excluded. All dependent variables are scaled by consolidated assets. The dependent variables ΔPen Debt, ΔLT Debt, Δ Tot Debt are the changes in pension obligations, long-term financial debt, and total debt (sum of pension obligations, long-term, and short-term debt) respectively. $Pen\ Deficit$ represents the underfunded status of the pension plan (liabilities less assets). MTB is the log of market value of equity, less book value of equity, plus balance sheet assets divided by balance sheet assets. $Total\ Assets$ is the log of balance sheet assets. ROA is defined as net income divided by balance sheet assets. $Collateral$ is the ratio of net property plant and equipment to balance sheet assets. $LumpsumYear$ is a indicator variable equal to one for any firm-year where a sponsor offered a lumpsum buyout. Year fixed-effects are included in each specification. Standard errors are clustered at the firm-level.

	(1) ΔPen Debt/Cons At	(2) ΔLT Debt/Cons At	(3) Δ Tot Debt /Cons At	(4) ΔPen Debt/Cons At	(5) ΔLT Debt/Cons At	(6) Δ Tot Debt/Cons At
$Year_{t-3+}$	0.003	0.001	0.003	0.004	0.003	0.001
	(1.17)	(0.19)	(0.95)	(0.34)	(0.37)	(0.21)
$Year_{t-2}$	-0.001	0.023**	0.010	-0.029***	-0.020	-0.022*
	(-0.20)	(1.99)	(1.39)	(-2.65)	(-1.24)	(-1.75)
$Year_0$	-0.043***	0.007	-0.008	-0.047***	-0.023*	-0.031***
	(-3.34)	(0.86)	(-1.08)	(-3.85)	(-1.72)	(-2.72)
$Year_{t+1}$	0.003	0.017*	0.016	-0.012	-0.001	-0.001
	(0.55)	(1.68)	(1.58)	(-0.71)	(-0.11)	(-0.11)
$Year_{t+2}$	-0.008*	0.009	0.004	-0.004	-0.057	0.002
	(-1.73)	(0.94)	(0.46)	(-0.21)	(-0.98)	(0.17)
$Year_{t+3+}$	-0.009	0.002	-0.002	0.023	0.023	-0.033
	(-1.54)	(0.18)	(-0.30)	(0.77)	(1.28)	(-0.77)
$\Delta Pen\ Deficit$	1.594***	-0.116	0.906***	1.683***	-0.077	0.976***
	(7.45)	(-0.96)	(6.59)	(7.65)	(-0.46)	(7.29)
ΔMTB	0.013	-0.032***	-0.027**	0.018**	0.015	0.020
	(1.28)	(-2.78)	(-2.48)	(2.58)	(0.68)	(0.94)
$\Delta BS\ Assets$	-0.057***	0.009	-0.014	-0.053***	0.053**	0.029
	(-3.11)	(0.58)	(-0.85)	(-3.73)	(2.28)	(1.35)
ΔROA	0.024	-0.161***	-0.183***	-0.039**	-0.191***	-0.229***
	(1.17)	(-6.77)	(-8.54)	(-2.19)	(-3.85)	(-5.07)
$\Delta Collateral$	0.123***	0.051	0.064	0.026	0.158	0.077
	(3.09)	(0.72)	(0.93)	(0.85)	(1.54)	(0.78)
$LumpsumYear$	-0.010**	-0.002	-0.009*	-0.028***	0.022	0.001
	(-2.16)	(-0.30)	(-1.79)	(-3.39)	(0.89)	(0.06)
$Constant$	0.003***	0.010***	0.011***	0.005***	0.005**	0.010***
	(2.71)	(8.36)	(8.72)	(3.93)	(2.00)	(4.19)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.484	0.063	0.174	0.362	0.084	0.184
Observations	2206	2206	2206	1981	1981	1981

t statistics in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A.4: **Variance Decomposition**

This table reports the results of a regression of the cash flow (CF News) and discount rate news (DF News) components on a series of quarter indicators relative to the pension buyout event date. Qtr_0 represents the event quarter. The return decomposition of [16] described in Section subsection 1.5.1 is used to derive the unique components of returns. Both firm and year-quarter fixed effects are used in each specification.

	(1) CF News	(2) DR News
Qtr_{t-3+}	0.014	0.000
	(1.02)	(0.11)
Qtr_{t-2}	0.026	0.000
	(1.47)	(0.23)
Qtr_0	-0.040**	-0.003
	(-2.24)	(-1.42)
Qtr_{t+1}	0.024	0.001
	(1.31)	(0.37)
Qtr_{t+2}	-0.005	0.001
	(-0.27)	(0.62)
Qtr_{t+3}	0.000	-0.001
	(0.01)	(-0.56)
Qtr_{t+4}	0.005	-0.000
	(0.27)	(-0.03)
Qtr_{t+4+}	-0.009	-0.000
	(-0.65)	(-0.07)
Constant	-0.007	0.000
	(-0.51)	(0.11)
Firm FE	Yes	Yes
Quarter FE	Yes	Yes
R-squared	0.036	0.063
Observations	4230	4230

t statistics in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

APPENDIX B

PENSION OVERHANG AND CORPORATE INVESTMENT

Table B.1: **Variable Description**

Variable	**Source**	**Description**
Tobin's Q	Compustat	(at - ceq - txdb + csho*prcc_f) / at
Cash flow	Compustat	ni + dp + xpr
Credit Ratings	Compustat; S&P	Long-term credit rating
Beta	CRSP, Compustat	Regressions of stock returns on vwretd
Assets	Compustat	at
Debt/Assets	Compustat	dt/at
Market/Book	Compustat	(at+mkvalt-teq)/at
Interest Coverage	Compustat	EBITDA / xint
EBITDA/Sales	Compustat	EBITDA / revt
Plan Funded Status	Form 5500	Line 14
Mandatory (Employer) Contributions	Form 5500	Line 34
Plan Liabilities	Form 5500	Line 3d
Debt Overhang	Compustat; Form 5500; Moody's; Altman and Kishore (1996)	See equation (2)
Pension Overhang	Compustat; Form 5500; Moody's; Altman and Kishore (1996)	See equation (3)
High Tax Rate	John Graham Website	Marginal tax rates

Table B.2: **Correlations**

This table presents pairwise Pearson correlations between $Investment$, $Tobin's\ Q$, $Cash\ flow$, $Employer\ Contributions$, $Overhang$, and the novel measure of pension overhang, $Pension\ Overhang$. Investment is capital expenditures scaled by lagged capital stock, Tobin's Q is the market value of equity plus the book value of debt divided by the book value of assets. Tobin's Q is lagged one year. The cash flow variable is constructed following [12] to account for non-cash pension expense. Cash flow is scaled by lagged capital stock. Employer contributions are reported in plan Form 5500 filings and aggregated to the firm level.

	Investment	Tobin's Q	Cash flow	Employer Contributions	Overhang	Pension Overhang
Investment	1.00	0.27	0.40	0.03	0.01	-0.10
Tobin's Q	0.27	1.00	0.43	0.04	-0.17	-0.14
Cash flow	0.40	0.43	1.00	0.12	-0.05	-0.07
Employer Cont.	0.03	0.04	0.12	1.00	0.13	0.53
Overhang	0.01	-0.17	-0.05	0.13	1.00	0.30
Pension Overhang	-0.10	-0.14	-0.07	0.53	0.30	1.00

Table B.3: **Measurement Error Consistent Estimation**

This table presents the incremental effects of pension overhang using the higher-order cumulants estimator of Erickson, Jiang, and Whited (2014). This estimator is robust to measurement errors in Tobin's Q. The equation estimated is

$$\frac{I_{i,t}}{K_{i,t-1}} = \alpha_i + \eta_t + \beta_1 Q_{i,t-1} + \beta_2 \frac{CF_{i,t}}{K_{i,t-1}} + \beta_3 Overhang_{i,t} + \beta_4 Pension\ Overhang_{i,t} + \epsilon_{i,t}$$

All variables are defined in the Appendix. Low (High) Overhang is an indicator variable equal to 1 if the firm-year is in the lower (top) tercile of Overhang. The highest order of cumulants used in all regressions is 5.

	(1) Capx/PPE$_{t-1}$	(2) Capx/PPE$_{t-1}$	(3) Capx/PPE$_{t-1}$	(4) Capx/PPE$_{t-1}$	(5) Capx/PPE$_{t-1}$	(6) Capx/PPE$_{t-1}$
Tobin's Q	0.175***	0.188***	0.187***	0.184***	0.189***	0.188***
	(4.816)	(6.586)	(6.822)	(6.670)	(6.747)	(6.747)
Cashflow	-0.014	-0.022**	-0.023**	-0.022**	-0.023**	-0.023**
	(-1.241)	(-2.032)	(-2.139)	(-2.109)	(-2.149)	(-2.156)
Overhang		-0.068		-0.052		
		(-0.946)		(-0.742)		
Low Overhang					-0.002	-0.001
					(-0.619)	(-0.608)
High Overhang					-0.002	-0.002
					(-0.858)	(-0.828)
Pension Overhang			-1.065***	-1.014***	-1.060***	-1.105***
			(-4.115)	(-3.751)	(-4.080)	(-4.074)
Employer Contributions						0.030
						(0.524)
Firm	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3190	1964	1967	1964	1964	1964
ρ^2	0.25	0.33	0.34	0.34	0.34	0.34

* p <0.10, ** p <0.05, *** p <0.01

Table B.4: **Robustness: Deflating by Assets**

This table estimates difference-in-differences analysis of capital expenditures around MAP-21 similar to Table Table 2.3 except now all variables are scaled by assets. $HighPenOverhang$ is an indicator variable that takes the value of 1 if a firm falls above the median $Pension\ Overhang$ in the year prior to MAP-21. $Post$ is an indicator variable for all years after the passage of the legislation (2012). $Underfunded$ is an indicator equal to 1 if a firm's WAFS was under 70% in the year prior to MAP-21. We control for $Tobin's\ Q$, $Cashflow$, $Overhang$, $EmployerContributions$. Tobin's Q is the market value of equity plus the book value of debt divided by the book value of assets. Tobin's Q is lagged one year. The cash flow variable is constructed following [12] to account for non-cash pension expense. Employer contributions are reported in plan Form 5500 filings and aggregated to the firm level.

	(1) Capex/Assets$_{t-1}$	(2) Capex/Assets$_{t-1}$	(3) Capex/Assets$_{t-1}$
HighPenOverhang × Post	0.006*	0.006**	
	(1.850)	(2.048)	
Underfunded × Post			0.005
			(0.986)
Tobin's Q	0.015***	0.014***	0.015***
	(5.147)	(4.100)	(5.097)
Cashflow	0.048**	0.055***	0.051**
	(2.441)	(2.607)	(2.500)
Overhang	−0.087	−0.083	−0.095
	(−0.993)	(−0.975)	(−1.080)
Employer Contributions	0.096	0.379**	0.043
	(0.550)	(2.398)	(0.278)
Firm	Yes	Yes	Yes
Year	Yes	Yes	Yes
Industry × Year	No	Yes	No
Observations	1,873	1,873	1,910
Within R^2	0.11	0.09	0.10
Adj. R^2	0.75	0.75	0.75

Clustering for standard errors at the firm-level for all specifications.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table B.5: **Robustness: Difference-in-Differences**

In this table we test the robustness of our difference-in-differences analysis of capital expenditures scaled by lagged capital stock:

$$\frac{I_{i,t}}{K_{i,t-1}} = \alpha_i + \eta_t + \beta_1 (High\,Overhang \times Post) + \beta_2 Q_{i,t-1} + \beta_3 \frac{CF_{i,t}}{K_{i,t-1}} + \beta_4 Overhang_{i,t} + \beta_5 Contributions_{i,t} + \epsilon_{i,t}$$

$High\ Overhang$ is an indicator variable that takes the value of 1 if a firm has an average $Pension\ Overhang$ in the period prior to MAP-21 (2009-2011) above the median average value for all firms. $Post$ is an indicator variable for all years after the passage of the legislation (2012). We control for $Tobin's\ Q$, $Cashflow$, $Overhang$, $EmployerContributions$. Tobin's Q is the market value of equity plus the book value of debt divided by the book value of assets. Tobin's Q is lagged one year. The cash flow variable is constructed following [12] to account for non-cash pension expense. Cash flow is scaled by lagged capital stock. Employer contributions are reported in plan Form 5500 filings and aggregated to the firm level.

	(1) Capex/PPE$_{t-1}$	(2) Capex/PPE$_{t-1}$
High Overhang × Post	0.019***	0.020***
	(2.728)	(2.786)
Tobin's Q	0.057***	0.051***
	(7.980)	(6.999)
Cashflow	0.019***	0.026***
	(2.608)	(3.482)
Overhang	−0.085	−0.080
	(−1.418)	(−1.344)
Employer Contributions	−0.045	0.060
	(−0.776)	(0.891)
Firm	Yes	Yes
Year	Yes	No
Industry × Year	No	Yes
Observations	1,913	1,913
Within R^2	0.2	0.16
Adj. R^2	0.66	0.64

Clustering for standard errors at the firm-level for all specifications.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table B.6: **Summary Statistics - Matched Sample**

This table presents summary statistics for our matched sample. The group of high pension overhang firms are matched with companies with low pension overhang. We match on the average of Tobin's Q, cash flow, and total assets in the period before MAP-21 (2009 to 2011). Panel A presents summary statistics of firm averages during the period before MAP-21 for the full sample, while Panel B presents summary statistics for the low overhang control firms and high overhang firms. The last column in the table is the p-value from the null hypothesis that the average across the two groups is the same.

	Low Overhang			High Overhang			
	Mean	Median	Std. Dev.	Mean	Median	Std. Dev.	p-value
Panel A: Full sample							
Tobin's Q	1.656	1.434	0.657	1.362	1.246	0.415	0.000
Cash flow	0.645	0.540	0.527	0.556	0.436	0.521	0.151
Total Assets	22,568	8,078	42,581	10,410	3,409	22,944	0.003
Panel B: Matched sample							
Tobin's Q	1.443	1.325	0.507	1.362	1.246	0.415	0.249
Cash flow	0.575	0.403	0.529	0.556	0.436	0.521	0.806
Total Assets	13,830	5,280	26,014	10,410	3,409	22,944.	0.350

Table B.7: **Financial Constraints and Pension Overhang**

This table displays regression results including interaction terms for various measures of firm financial constraints. *High* designates a firm falling above the median for each financial constraint proxy in the year prior to MAP-21. The $Size - Age$ Index is defined in accordance with [44]. $Hoberg - Maksimovik$ represents the financing constraints index based on textual analysis of [45]. $Cash$ references cash and cash equivalents scaled by total assets. $Small$ references firm size based on total assets. $Post$ is an indicator variable for all years after the passage of the legislation (2012). We control for $Tobin's\ Q$, $Cash\ flow$, $Overhang$, $Employer\ Contributions$. Tobin's Q is the market value of equity plus the book value of debt divided by the book value of assets. Tobin's Q is lagged one year. The cash flow variable is constructed following Rauh (2006) to account for non-cash pension expense. Cash flow is scaled by lagged capital stock. Employer contributions are reported in plan Form 5500 filings and aggregated to the firm level.

	(1) Capex/PPE$_{t-1}$	(2) Capex/PPE$_{t-1}$	(3) Capex/PPE$_{t-1}$	(4) Capex/PPE$_{t-1}$
High Overhang × Post × High Size-Age	0.032** (2.023)			
High Overhang × Post × High Hoberg-Maksimovic		0.029 (1.573)		
High Overhang × Post × High Cash			0.042*** (3.115)	
High Overhang × Post × Small				0.028 (1.344)
High Overhang × Post	0.013* (1.698)	0.008 (0.817)	0.001 (0.090)	0.012* (1.683)
Tobin's Q	0.058*** (8.093)	0.059*** (6.510)	0.058*** (8.162)	0.058*** (7.912)
Cashflow	0.019*** (2.721)	0.021** (2.238)	0.018** (2.502)	0.018*** (2.617)
Overhang	−0.075 (−1.278)	−0.067 (−1.009)	−0.069 (−1.167)	−0.083 (−1.481)
Employer Contributions	−0.031 (−0.510)	−0.044 (−0.574)	−0.037 (−0.640)	−0.032 (−0.565)
Post × High Size-Age	−0.002 (−0.173)			
Post × High Hoberg-Maksimovic		−0.008 (−0.726)		
Post × High Cash			−0.009 (−1.006)	
Post × Small				0.002 (0.138)
Firm	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Observations	1,854	1,368	1,873	1,873
Within R^2	0.21	0.23	0.22	0.21
Adj. R^2	0.66	0.66	0.66	0.66

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table B.8: **CEO compensation**

This table displays regression results including interaction terms for various measures of incentives in CEO compensatio. *High Delta* (*High Vega*) designates a firm with above median Delta (Vega) in CEO compensation in the year prior to MAP-21. $Post$ is an indicator variable for all years after the passage of the legislation (2012). We control for $Tobin's\ Q$, $Cash\ flow$, $Overhang$, $Employer\ Contributions$. Tobin's Q is the market value of equity plus the book value of debt divided by the book value of assets. Tobin's Q is lagged one year. The cash flow variable is constructed following Rauh (2006) to account for non-cash pension expense. Cash flow is scaled by lagged capital stock. Employer contributions are reported in plan Form 5500 filings and aggregated to the firm level.

	(1) Capex/PPE$_{t-1}$	(2) Capex/PPE$_{t-1}$	(3) Capex/PPE$_{t-1}$
High Overhang × Post × High Delta	0.027*		
	(1.788)		
High Overhang × Post × High Vega		0.038**	
		(2.387)	
High Overhang × Post × High Option Vesting Horizon			0.031**
			(1.991)
High Overhang × Post	0.004	−0.002	0.006
	(0.371)	(−0.146)	(0.486)
Tobin's Q	0.051***	0.050***	0.052***
	(7.973)	(7.856)	(6.221)
Cashflow	0.021***	0.020**	0.021**
	(2.598)	(2.538)	(2.418)
Overhang	−0.058	−0.055	−0.146**
	(−0.714)	(−0.700)	(−2.491)
Employer Contributions	−0.032	−0.031	0.003
	(−0.473)	(−0.467)	(0.056)
Post × High Delta	−0.023**		
	(−2.430)		
Post × High Vega		−0.025**	
		(−2.309)	
Post × High Option Vesting Horizon			−0.009
			(−1.017)
Firm	Yes	Yes	Yes
Year	Yes	Yes	Yes
Observations	1,513	1,513	1,252
Within R^2	0.19	0.19	0.2
Adj. R^2	0.68	0.68	0.67

Clustering for standard errors at the firm-level for all specifications.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

APPENDIX C

DEFAULT RISK AND THE PRICING OF U.S. SOVEREIGN BONDS

C.1 Appendix

C.1.1 Variable Descriptions

- HPW Noise, the measure of arbitrage capital availability proposed in [101]. This measure is constructed as the root mean squared error in the observed yields of Treasury securities relative to those implied by a Nelson-Siegel-Svensson zero coupon curve across the term structure.[1] The measure takes into account the close relationship between availability of arbitrage capital and liquidity. [66] posit that the inability of arbitrageurs to immediately eliminate arbitrage may have resulted in the divergence between nominal and inflation-protected securities markets. They suggest that this slow-moving capital hypothesis ([109] and [110]) may allow arbitrage profits to persist. This HPW measure, which averages 3.52 basis points, rises to 20.47 basis points during the financial crisis.

- TIPS Noise, is the absolute average fitting error of the Nelson-Siegel-Svensson model estimated on the TIPS yield curve (see [100]). This variable mimics the HPW Noise measure for the TIPS market as opposed to nominal Treasuries. The series is obtained from the Board of Governors of the Federal Reserve and is computed at the daily frequency.[2] The series move between 0bps and 5 bps before the crisis, spike to 40 bps in late 2008 and average about 5 bps afterward. Since it represents the relative liquidity of TIPS, this measure is well-fitted to control for the slowly moving capital hypothesis of [66].

[1] These data are obtained from Jun Pan's webpage, http://www.mit.edu/~junpan/

[2] We thank Richard Crump for providing us access to the data.

- LIBOR-OIS, the spread between LIBOR and the overnight indexed swap rate. As shown in Table 3.1, this spread, which averages 35 basis points over our sample, rose to 364 basis points during the crisis. This rise has been attributed to an increase in perceived counterparty credit risk in financial markets. [66] suggest that their arbitrage profits could arise due to counterparty credit risk, especially if nominal Treasuries are viewed as safe haven assets. However, the authors suggest it is an unlikely explanation for their findings due to the collateralization of of swap contracts ([93]).

- OTR Difference, the yield difference between the 10-year off-the-run GSW par yield and the generic 10-year on-the-run yield from Bloomberg. During periods of stress, market participants may seek the most liquid securities, on-the-run government benchmark bonds, which accordingly often trade at a premium to an equivalent off-the-run bond.

- VIX, the CBOE volatility index. The VIX is often viewed as a measure of the market's perception of the quantity and/or price of risk in equity markets specifically, and financial markets as a whole. However, [111] suggests that an increase in the VIX is associated with a higher premium for liquidity provision, and therefore a reduction in the amount of liquidity in the financial system. The VIX averages 22% over our sample period, with an increase to nearly 81% during the financial crisis.

C.1.2 Empirical Robustness

Pflueger and Viceira explanatory variables

In the approach of [86], liquidity is proxied using three variables: the off-the-run spread (OTR), log relative volume in the TIPS and nominal Treasury markets (VOL), and the synthetic-cash spread, which is our variable ILS-BEI.In their main results, [86] use the asset swap spread and use the ILS-BEI for robustness. Results using both variables are similar, and we use the ILS-BEI for simplicity and to complement our earlier results. The off-the-run spread is the difference between the 10 year off-the-run par yield and the 10-year on-the-run nominal yield from Bloomberg (USGG10YR). Relative volume in the two markets is measured using primary dealers' transaction volume from the New York Federal Reserve FR-2004 survey. Inflation expectations are measured using two variables, the median 10-year CPI forecast from the Survey of Professional Forecasters (CPI^e) and the Chicago Fed National Activity Index ($CFNAI$). The CPI forecast is available quarterly, and the $CFNAI$ is available monthly. We create a daily series using the most recently released data.Our results are similar in terms of signs and magnitude regardless of the data frequency; we also examine weekly and monthly data. However, statistical significance of some of the coefficients declines as we sample at coarser data frequencies.

Cheapest-to-Deliver

In the case of a credit event, the cheapest-to-deliver (CtD) obligation of the reference entity (here, the U.S. sovereign) will be a key determinant of the recovery rate on the underlying asset. In the auction process described in Section subsection 3.2.2, all obligations deemed *deliverable* by the Determinations Committee are eligible to be sold. The protection buyer is incentivized to deliver the cheapest outstanding reference obligation and hence the final price at auction will largely be determined by the prevailing dealer quotes of this obligation. Therefore, CDS premia and the expected price of the CtD obligation would be expected to have a negative correlation. The CtD obligation may vary considerably over time and depend on the sovereign distance to default.

We examine the effects of CtD empirically in Table C.1. We assume the general methodology of [92] to identify the cheapest nominal Treasury on each day of our sample and include the following as a control variable:

$$CtD_t = 100 - \min(Price_t).$$

The regression result is essentially unchanged from our primary specification in Table 3.2. In Column (1), CtD shows a weak, insignificant relationship with changes in ILS-BEI. The coefficient on CtD is negative and significant in Column (3) where we include all controls as well as a week and tenor fixed effect. Based on the construction of the CtD variable, a lower nominal bond price (higher yield) on any day is associated with a higher value of CtD. The results suggest higher Treasury yields are consistent with a narrower ILS-BEI, yet the coefficient on US CDS is essentially unchanged. There exists some ambiguity over what would be considered a deliverable obligation in the case of a sovereign credit event as this would ultimately be decided by the Determinations Committee. It is with minimal disagreement that nominal bonds up to a 30-year maturity would be accepted, yet the role of inflation-linked bonds, zero-coupon STRIPS, or sovereign guarantees (where U.S. sovereign gurantees the repayment of debt issued by another party) is less clear. Our empirical results are consistent whether we include or exclude TIPS in the definition of CtD.

Foreign Exchange Risk

Since the U.S. sovereign CDS contracts are denominated in euros, one could argue that there is foreign exchange risk embedded in CDS contracts which is also driving the variability in the changes in ILS-BEI. As noted by [67], it makes sense for an investor looking for a protection against a U.S. default to obtain a payment in euros instead of dollars since it is likely that the dollar would greatly depreciate. The market for EUR-denominated CDSs is therefore more liquid than for USD-denominated CDSs. This gives rise to a so-called *quanto spread* that has been exploited to measure the depreciation risk upon default. To rule out euro-dollar exchange rate risk as an omitted variable in our baseline results, we perform panel regressions controlling for the exchange rate (risk) between the two currencies: the 5-year EURUSD basis swap spread ($EURUSD$) and the spot exchange rate ($Spot$) between the two currencies.

Table C.2 summarizes the results. In columns (1) and (2), we regress changes in ILS-BEI on U.S. CDS spread, and $EURUSD$ or $Spot$, respectively. In Columns (3) and (4), we repeat the regressions after adding the same control variables as those used in Table 3.2. Examining the coefficient loadings on U.S. CDS in the first row, we see that they are all positive and statistically significant across the board. The results presented in Table C.2 of the Appendix are essentially unchanged and the coefficient on the CDS ranges from 0.18 to 0.24, as in our baseline specification. We conclude the exchange rate risk in euro CDS contracts is not driving our results.

[66] Mispricing

Another measure of the relative pricing of nominal bonds vs. real bonds can be found in [66]. The authors replicate a nominal bond by matching the cash flows using a basket of inflation swaps, Treasury Strips, as well as a TIPS with similar maturity and coupon dates. In the absence of any market frictions, the price of the nominal bond and the price of the basket of replicating assets should be exactly the same. Surprisingly, this is not the case in the data, and we refer to the difference as Treasury-TIPS mispricing. [66] document persistent mispricing between 2004 and 2009 in their sample that can be as high as $20 per $100 notional. We reproduce the matched bond pairs from their study and extend the sample period to 2015. We document that mispricing remains in the sample after the financial crisis, and it averages about $3 per $100 notional across bond pairs and across time.

We then perform our baseline panel regressions after replacing ILS-BEI with pairwise mispricing as the dependent variable. The results are shown in Table C.3, which has a similar format as Table 3.2 with two exceptions. First, we add time-to-maturity (TTM) as a control variable in the panel. Second, instead of using a tenor fixed effect, column (7) employs a bond pair fixed effect. We also divide mispricing by 100 to convert mispricing from dollars to cents per $1 notional. Similar to the first row of Table 3.2, the estimated coefficients on U.S. CDS are positive and statistically significant under all specifications in Table C.3. In Columns (6) and (7), with a full slate of control variables, a 1% increase in the CDS spread implies a 0.4 cent increase in the mispricing. This means the nominal bond trades approximately 40 cents rich compared to the basket of inflation swaps, Strips, and TIPS, per $100 notional. This is also economically significant if you consider that the average mispricing is about $3. Using the relative pricing of nominal and real bonds from [66], we show that sovereign default risk embedded in CDS contracts is strongly correlated with the price differential between Treasury and TIPS. The direction of impact is also consistent with the effect on ILS-BEI: higher CDS spreads are associated with greater downward pressure on TIPS prices relative to Treasury prices.

Repo Premium

[112] suggest the repo special spread for Treasury securities can aid in explaining numerous fixed income anomalies documented in the literature. Particularly during times of market stress, investors place a premium on the most liquid instruments resulting in a time-varying special collateral risk premium.[3] In Table C.4 we test whether the repo premium plays a role in explaining the ILS-BEI spread. Based on data availability, the sample spans from January 2009 to October 2015. The coefficient on the repo premium is positive, but statistically insignificant across specifications. This is driven by the crisis era, which would be consistent with narrower Treasury yields, tigher BEI and hence a wider ILS-BEI spread. In untabulated results, we use the sample period beginning in 2010 and witness a negative, insignificant relationship between repo premiums and the ILS-BEI spread while coefficients on US CDS spreads are consistent with Table 3.6. It is possible that our use of zero-coupon smoothed yield curves to measure the ILS-BEI spread reduces the correlation with the repo premium that was derived from the cross-sections of outstanding Treasury securities.

[3]We thank Stefania D'Amico for this suggestion and Aaron Pancost for providing the data

TIPS Deflation Floors

One feature of TIPS that potentially can produce differential pricing relative to nominal Treasury bonds is the fact that it has a deflation floor. In our study, we show that the BEI spread narrows (ILS-BEI widens) when the CDS spread widens. To the extent that the U.S. CDS spread captures sovereign default risk of the U.S. government, this implies TIPS yields rise more than nominal yields when default risk is elevated. However, if it is the case that the option value of the deflation floor on TIPS is more valuable when default risk is high because deflation is more likely to happen during downturns, then the deflation floor on TIPS actually puts downward pressure on real yields in bad times. Therefore, the fact that we still see a narrowing of the BEI in the data when the CDS spread widens suggests that factors other than the deflation floor feature are driving the wedge between real and nominal bond prices.

C.1.3 Affine property and conditional moments of w_t

Let us compute the physical conditional moment-generating function of w_t applied in $u = \left(u_x',\, u_y',\, u_\delta'\right)'$.

$$
\begin{aligned}
\varphi_{w_t}^{\mathbb{P}}(u) &:= \mathbb{E}_t^{\mathbb{P}}\left[\exp\left(u' w_{t+1}\right)\right] \\
&= \exp\left\{u_x'\left(\mu + \Phi x_t\right) + \frac{1}{2} u_x' \Sigma u_x\right\} \mathbb{E}_t^{\mathbb{P}}\left\{\mathbb{E}_t^{\mathbb{P}}\left[\exp\left(u_y' y_{t+1} + u_\delta' \delta_{t+1}\right) \middle| y_{t+1}\right]\right\} \\
&= \exp\left\{u_x'\left(\mu + \Phi x_t\right) + \frac{1}{2} u_x' \Sigma u_x\right\} \mathbb{E}_t^{\mathbb{P}}\left[\exp\left(\left(\beta_\lambda \frac{\operatorname{diag}(\mathsf{c}_\delta) u_\delta}{\mathbf{1} - \operatorname{diag}(\mathsf{c}_\delta) u_\delta} + u_y\right)' y_{t+1}\right)\right]
\end{aligned}
$$

where the fraction is an abuse of notation for an element by element ratio and:

$$
\beta_\lambda = \begin{pmatrix} \beta_\lambda^{(c)} & \mathbf{0} \\ \mathbf{0} & \beta_\lambda^{(\ell)} \end{pmatrix}.
$$

Thus, denoting by $\widetilde{u}_y = \left(\beta_\lambda \frac{\mathrm{diag}(\mathsf{c}_\delta)u_\delta}{\mathbf{1}-\mathrm{diag}(\mathsf{c}_\delta)u_\delta} + u_y\right)$, we have:

$$\varphi^{\mathbb{P}}_{w_t}(u) = \exp\left\{u_x'\left(\mu + \Phi x_t\right) + \frac{1}{2}u_x'\Sigma u_x + \left(\frac{\mathrm{diag}(\mathsf{c}_y)\widetilde{u}_y}{\mathbf{1}-\mathrm{diag}(\mathsf{c}_y)\widetilde{u}_y}\right)'\beta_y\, y_t - \nu'\log\left[\mathbf{1}-\mathrm{diag}(\mathsf{c}_y)\widetilde{u}_y\right]\right\}\,, \tag{C.1}$$

which is an exponential-affine function of x_t and y_t, thus of w_t by extension. The conditional mean of w_t is then given by:

$$\begin{aligned}
\mathbb{E}^{\mathbb{P}}_t\left(x_{t+1}\right) &= \mu + \Phi\, x_t \\
\mathbb{E}^{\mathbb{P}}_t\left(y_{t+1}\right) &= \mathrm{diag}(\mathsf{c}_y)\left(\nu + \beta_y\, y_t\right) \\
\mathbb{E}^{\mathbb{P}}_t\left(\delta_{t+1}\right) &= \mathbb{E}^{\mathbb{P}}_t\left[\mathbb{E}^{\mathbb{P}}_t\left(\delta_{t+1}\middle|y_{t+1}\right)\right] = \mathrm{diag}(\mathsf{c}_\delta)\beta_\lambda'\mathbb{E}^{\mathbb{P}}_t\left(y_{t+1}\right)\,.
\end{aligned}$$

For notational convenience, we introduce the block matrix Q of size $N \times N$ defined as:

$$\begin{pmatrix} I_{N_x} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathrm{diag}\left(\mathsf{c}_y\right) & \mathbf{0} \\ \mathbf{0} & \mathrm{diag}\left(\mathsf{c}_\delta\right)\,\beta_\lambda\,\mathrm{diag}\left(\mathsf{c}_y\right) & \mathrm{diag}\left(\mathsf{c}_\delta\right) \end{pmatrix}$$

We obtain that

$$\mathbb{E}^{\mathbb{P}}_t(w_{t+1}) = \Psi_0 + \Psi\, w_t\,,$$

where:

$$\Psi_0 = Q \times \begin{pmatrix} \mu \\ \nu \\ \mathbf{0} \end{pmatrix} \quad \text{and} \quad \Psi = Q \times \begin{pmatrix} \Phi & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \beta_y & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} \end{pmatrix}\,. \tag{C.2}$$

Let us now turn to the conditional variance. x_t is independent from y_t and δ_t, and its conditional covariance matrix is given by Σ. Then, using the properties of gamma variables, we have:

$$\mathbb{V}^{\mathbb{P}}_t\left(y_{t+1}\right) = \mathrm{diag}\left(\mathsf{c}_y\right)^2 \times \mathrm{diag}\left(\nu + 2\beta_y\, y_t\right)\,.$$

Using the law of total variance, we can express the conditional variance of δ_t as:

$$\begin{aligned}
\mathbb{V}_t^{\mathbb{P}}\left(\delta_{t+1}\right) &= \mathbb{V}_t^{\mathbb{P}}\left[\mathbb{E}_t^{\mathbb{P}}\left(\delta_{t+1}\middle|y_{t+1}\right)\right] + \mathbb{E}_t^{\mathbb{P}}\left[\mathbb{V}_t^{\mathbb{P}}\left(\delta_{t+1}\middle|y_{t+1}\right)\right] \\
&= \mathbb{V}_t^{\mathbb{P}}\left[\mathrm{diag}\left(\mathsf{c}_\delta\right)\beta_\lambda'\, y_{t+1}\right] + \mathbb{E}_t^{\mathbb{P}}\left[2\mathrm{diag}\left(\mathsf{c}_\delta\right)^2 \mathrm{diag}\left(\beta_\lambda'\, y_{t+1}\right)\right] \\
&= \mathrm{diag}\left(\mathsf{c}_\delta\right)\beta_\lambda'\, \mathbb{V}_t^{\mathbb{P}}(y_{t+1})\,\beta_\lambda \mathrm{diag}\left(\mathsf{c}_\delta\right) + 2\mathrm{diag}\left(\mathsf{c}_\delta\right)^2 \mathrm{diag}\left(\beta_\lambda'\, \mathbb{E}_t^{\mathbb{P}}\left[y_{t+1}\right]\right) \\
&= \mathrm{diag}\left(\mathsf{c}_\delta\right)\beta_\lambda'\, \mathbb{V}_t^{\mathbb{P}}(y_{t+1})\,\beta_\lambda \mathrm{diag}\left(\mathsf{c}_\delta\right) + 2\mathrm{diag}\left(\mathsf{c}_\delta\right)^2 \mathrm{diag}\left[\beta_\lambda'\, \mathrm{diag}\left(\mathsf{c}_y\right)\left(\nu + \beta_y\, y_t\right)\right]\ .
\end{aligned}$$

Last, the conditional covariance between y_t and δ_t is given by:

$$\begin{aligned}
\mathbb{C}ov_t^{\mathbb{P}}\left(y_{t+1},\, \delta_{t+1}\right) &= \mathbb{C}ov_t^{\mathbb{P}}\left(y_{t+1},\, \mathbb{E}_t^{\mathbb{P}}\left[\delta_{t+1}\middle|y_{t+1}\right]\right) + \mathbb{E}_t^{\mathbb{P}}\left[\mathbb{C}ov_t^{\mathbb{P}}\left(y_{t+1},\, \delta_{t+1}\middle|y_{t+1}\right)\right] \\
&= \mathbb{C}ov_t^{\mathbb{P}}\left(y_{t+1},\, \mathrm{diag}\left(\mathsf{c}_\delta\right)\beta_\lambda'\, y_{t+1}\right) \\
&= \mathbb{V}_t^{\mathbb{P}}\left(y_{t+1}\right)\beta_\lambda\, \mathrm{diag}\left(\mathsf{c}_\delta\right)\ .
\end{aligned}$$

Putting all results together, we obtain:

$$\Omega_{t-1} = \mathbb{V}_t^{\mathbb{P}}\left(w_{t+1}\right) = Q \times \begin{pmatrix} \Sigma & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathrm{diag}\left(\nu + 2\beta_y\, y_t\right) & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & 2\mathrm{diag}\left[\beta_\lambda'\, \mathrm{diag}\left(\mathsf{c}_y\right)\left(\nu + \beta_y\, y_t\right)\right] \end{pmatrix} \times Q'\,. \tag{C.3}$$

We obtain unconditional moments by assuming stationarity of w_t:

$$\begin{aligned}
\mathbb{E}^{\mathbb{P}}\left(w_t\right) &= \left(I_N - \Psi\right)^{-1}\Psi_0 \\
\mathrm{Vec}\left[\mathbb{V}^{\mathbb{P}}\left(w_t\right)\right] &= \left[I_{N^2} - \left(Q\otimes Q\right)\left(\Psi\otimes\Psi\right)\right]^{-1} \times \left[\Omega_0 + \Omega\mathbb{E}^{\mathbb{P}}\left(y_t\right)\right]\ ,
\end{aligned}$$

where Ω_0 and Ω are such that:

$$\mathrm{Vec}\begin{pmatrix} \Sigma & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathrm{diag}\left(\nu + 2\beta_y\, y_t\right) & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & 2\mathrm{diag}\left[\beta_\lambda'\, \mathrm{diag}\left(\mathsf{c}_y\right)\left(\nu + \beta_y\, y_t\right)\right] \end{pmatrix} = \Omega_0 + \Omega y_t\,.$$

C.1.4 Affine risk-neutral property

To obtain the affine property under $\mathbb{Q}$ we need to proceed to the change of measure implied by the SDF specification of Equation (Equation 3.12). Since x_t is independent from y_t and δ_t and that the SDF does not incorporate cross-terms, we can proceed to its change of measure separately from that of $(y_t,\, \delta_t)$.

Our specification of x_t dynamics and the SDF that depends on x_t is that of a standard Gaussian affine term structure model with time varying prices of risk. We can thus directly apply the standard result that:

$$x_t = \mu^{\mathbb{Q}} + \Phi^{\mathbb{Q}} x_{t-1} + \sqrt{\Sigma}\,\varepsilon_t^{\mathbb{Q}}\,, \quad \text{where} \quad \varepsilon_t^{\mathbb{Q}} \sim \mathcal{N}\left(0, I_{N_x}\right)\,, \tag{C.4}$$

and the risk-neutral parameters are given by:

$$\mu^{\mathbb{Q}} = \mu + \Sigma\,\theta_{0,x}, \qquad \Phi^{\mathbb{Q}} = \Phi + \Sigma\,\Theta_x\,. \tag{C.5}$$

For the change of measure associated with the default and liquidity risk variables, we rely on Propositions 2.5-2.6 of [70], and we have that the risk-neutral intensities are equal to the physical intensities (there is no pricing of ”surprise”, i.e. the SDF does not depend on δ_t), and the risk-neutral dynamics of y_t is given by a vector autoregressive gamma process, such that:

$$y_t \,|\, y_{t-1} \overset{\mathbb{Q}}{\sim} \Gamma_\nu\left(\beta_y^{\mathbb{Q}}\, y_{t-1},\, \mathsf{c}_y^{\mathbb{Q}}\right) \,, \quad \text{where} \quad \beta_y^{\mathbb{Q}} = \beta_y \,\mathrm{diag}\left(\frac{\mathbf{1}}{\mathbf{1}-\mathrm{diag}(\theta_y)\,\mathsf{c}_y}\right), \quad \mathsf{c}_y^{\mathbb{Q}} = \frac{\mathsf{c}_y}{\mathbf{1}-\mathrm{diag}(\theta_y)\,\mathsf{c}_y}\,. \tag{C.6}$$

Hence, since the classes of distributions are the same under the risk-neutral measure, w_t is an affine process under the risk-neutral measure and its conditional moment generating function is given by:

$$\begin{aligned}
\varphi_{w_t}^{\mathbb{Q}}(u) &:= \mathbb{E}_t^{\mathbb{Q}}\left[\exp\left(u' w_{t+1}\right)\right] \\
&= \exp\left\{u_x'\left(\mu^{\mathbb{Q}} + \Phi^{\mathbb{Q}} x_t\right) + \frac{1}{2} u_x' \Sigma u_x + \left(\frac{\mathrm{diag}(\mathsf{c}_y^{\mathbb{Q}})\widetilde{u}_y^{\mathbb{Q}}}{\mathbf{1}-\mathrm{diag}(\mathsf{c}_y^{\mathbb{Q}})\widetilde{u}_y^{\mathbb{Q}}}\right)' \beta_y^{\mathbb{Q}}\, y_t - \nu' \log\left[\mathbf{1}-\mathrm{diag}(\mathsf{c}_y^{\mathbb{Q}})\widetilde{u}_y^{\mathbb{Q}}\right]\right\},
\end{aligned}$$

where

$$\widetilde{u}_y^{\mathbb{Q}} = \widetilde{u}_y = \left(\beta_\lambda \frac{\mathrm{diag}(\mathsf{c}_\delta) u_\delta}{\mathbf{1}-\mathrm{diag}(\mathsf{c}_\delta) u_\delta} + u_y\right)\,.$$

Building on the property of affine processes, we have that the multi-horizon moment generating function of w_t is also an exponential-affine function of w_t under the risk-neutral measure. Let us introduce the following notation:

$$\varphi_{w_t}^{\mathbb{Q}}(u) = \exp\left(A^{\mathbb{Q}}(u) + B^{\mathbb{Q}}(u)'\, w_t\right)\,.$$

We have that:

$$\varphi_{w_t}^{\mathbb{Q}}\left(u_1, \ldots, u_n\right) \;:=\; \mathbb{E}_t^{\mathbb{Q}}\left[\exp\left(\sum_{i=j}^{n} u_j'\, w_t\right)\right] = \exp\left[\mathcal{A}_n^{\mathbb{Q}}\left(u_1, \ldots, u_n\right) + \mathcal{B}_n^{\mathbb{Q}}\left(u_1, \ldots, u_n\right)'\, w_t\right]\,,$$

where $\mathcal{A}_0^{\mathbb{Q}}\left(u_1, \ldots, u_n\right) = \mathbf{0}$ and $\mathcal{B}_n^{\mathbb{Q}}\left(u_1, \ldots, u_n\right) = \mathbf{0}$ and the loadings are defined through the following recursions:

$$\begin{aligned}
\mathcal{A}_n^{\mathbb{Q}}\left(u_1, \ldots, u_n\right) &= A^{\mathbb{Q}}\left(u_1 + \mathcal{B}_{n-1}^{\mathbb{Q}}\left(u_2, \ldots, u_n\right)\right) + \mathcal{A}_{n-1}^{\mathbb{Q}}\left(u_2, \ldots, u_n\right) \\
\mathcal{B}_n^{\mathbb{Q}}\left(u_1, \ldots, u_n\right) &= B^{\mathbb{Q}}\left(u_1 + \mathcal{B}_{n-1}^{\mathbb{Q}}\left(u_2, \ldots, u_n\right)\right)\,.
\end{aligned}$$

Equation (Equation 3.16) defines this multi-horizon moment generating function when all $n-1$ first arguments are equal, i.e. $u_1 = u_2 = \ldots = u_{n-1} = u$ and $u_n = v$. Thus, our notation $\mathcal{A}_n^{\mathbb{Q}}(u,v)$ and $\mathcal{B}_n^{\mathbb{Q}}(u,v)$ can be obtained through the above recursions by calculating $\mathcal{A}_n^{\mathbb{Q}}(u,\ldots,u,v)$ and $\mathcal{B}_n^{\mathbb{Q}}(u,\ldots,u,v)$.

C.1.5 Pricing formulas for riskless nominal and real bonds

The price of riskless nominal bonds and TIPS is given by:

$$
\begin{aligned}
D_t^{(n)} &= \mathbb{E}_t^{\mathbb{Q}}\left[\exp\left(-\sum_{j=0}^{n-1} r_{t+j}\right)\right] = e^{-n\kappa_0^{(r)}}\mathbb{E}_t^{\mathbb{Q}}\left[\exp\left(-\sum_{j=0}^{n-1}\kappa^{(r)\prime}\, w_{t+j}\right)\right] \\
D_t^{*(n)} &= \mathbb{E}_t^{\mathbb{Q}}\left[\exp\left(-\sum_{j=0}^{n-1} r_{t+j} - \pi_{t+j+1}\right)\right] \\
&= e^{-n\left(\kappa_0^{(r)}-\kappa_0^{(\pi)}-\kappa^{(r)\prime}\, w_t\right)}\mathbb{E}_t^{\mathbb{Q}}\left[\exp\left(-\sum_{j=1}^{n-1}\left(\kappa^{(r)}-\kappa^{(\pi)}\right)'\, w_{t+j} + \kappa^{(\pi)\prime}\, w_{t+n}\right)\right].
\end{aligned}
$$

Thus, using our notation for the multi-horizon moment generating function of w_t under the risk-neutral measure, these expectations can be transformed as:

$$
\begin{aligned}
D_t^{(n)} &= \exp\left\{-n\kappa_0^{(r)} + \mathcal{A}_n^{\mathbb{Q}}\left(-\kappa^{(r)},\mathbf{0}\right) + \left[\mathcal{B}_n^{\mathbb{Q}}\left(-\kappa^{(r)},\mathbf{0}\right) - \kappa^{(r)}\right]'\, w_t\right\} \\
D_t^{*(n)} &= \exp\left\{-n\left(\kappa_0^{(r)}-\kappa_0^{(\pi)}\right) + \mathcal{A}_n^{\mathbb{Q}}\left(\kappa^{(\pi)}-\kappa^{(r)},\kappa^{(\pi)}\right) + \left[\mathcal{B}_n^{\mathbb{Q}}\left(\kappa^{(\pi)}-\kappa^{(r)},\kappa^{(\pi)}\right) - \kappa^{(r)}\right]'\, w_t\right\}.
\end{aligned}
$$

C.1.6 Pricing formulas for nominal treasuries and TIPS

Let us first focus on nominal bonds. We rewrite Equation (Equation 3.20) for convenience:

$$
\begin{aligned}
B_t^{(n)} &= \sum_{i=1}^{n}\mathbb{E}_t^{\mathbb{Q}}\left[\exp\left(-\sum_{j=0}^{i-1} r_{t+j}\right)\mathcal{P}_{t+i}^{(n_r)} \times \left(\mathbb{1}\left\{\sum_{j=0}^{i-1}\delta_{t+j}^{(c)} = 0\right\} - \mathbb{1}\left\{\sum_{j=0}^{i}\delta_{t+j}^{(c)} = 0\right\}\right)\right] \\
&\quad + \mathbb{E}_t^{\mathbb{Q}}\left[\exp\left(-\sum_{j=0}^{n-1} r_{t+j}\right)\mathbb{1}\left\{\sum_{j=0}^{n}\delta_{t+j}^{(c)} = 0\right\}\right].
\end{aligned}
$$

We start from the premise that the recovery payment is an exponential-affine function of w_t given by $\exp\left(\mathsf{A}_{n_r} + \mathsf{B}'_{n_r}\, w_t\right)$. Focusing on the first indicator term in the above equation, we can write:

$$
\begin{aligned}
& \mathbb{E}_t^{\mathbb{Q}}\left[\exp\left(-\sum_{j=0}^{i-1} r_{t+j}\right)\mathcal{P}_{t+i}^{(n_r)} \times \mathbb{1}\left\{\sum_{j=0}^{i-1}\delta_{t+j}^{(c)} = 0\right\}\right] \\
= \; & \mathbb{E}_t^{\mathbb{Q}}\left[\exp\left(\mathsf{A}_{n_r} + \mathsf{B}'_{n_r}\, w_{t+i} - i\kappa_0^{(r)} - \sum_{j=0}^{i-1}\kappa^{(r)\prime}\, w_{t+j}\right) \times \mathbb{1}\left\{\sum_{j=0}^{i-1}\delta_{t+j}^{(c)} = 0\right\}\right] .
\end{aligned}
$$

Using the lemma 3.1 of [70], we have:

$$
\begin{aligned}
& \mathbb{E}_t^{\mathbb{Q}}\left[\exp\left(\mathsf{A}_{n_r} + \mathsf{B}'_{n_r}\, w_{t+i} - i\kappa_0^{(r)} - \sum_{j=0}^{i-1}\kappa^{(r)\prime}\, w_{t+j}\right) \times \mathbb{1}\left\{\sum_{j=0}^{i-1}\delta_{t+j}^{(c)} = 0\right\}\right] \\
= \; & \lim_{\mathsf{u}\to+\infty} \mathbb{E}_t^{\mathbb{Q}}\left[\exp\left(\mathsf{A}_{n_r} + \mathsf{B}'_{n_r}\, w_{t+i} - i\kappa_0^{(r)} - \sum_{j=0}^{i-1}\left(\kappa^{(r)\prime}\, w_{t+j} + \mathsf{u}\delta_{t+j}^{(c)}\right)\right)\right] \\
= \; & \lim_{\mathsf{u}\to+\infty} \mathbb{E}_t^{\mathbb{Q}}\left[\exp\left(\mathsf{A}_{n_r} + \mathsf{B}'_{n_r}\, w_{t+i} - i\kappa_0^{(r)} - \sum_{j=0}^{i-1}\left(\kappa^{(r)} + \mathsf{u}\mathbf{e}_c\right)'\, w_{t+j}\right)\right] \\
= \; & \lim_{\mathsf{u}\to+\infty} \exp\left\{\mathsf{A}_{n_r} - i\kappa_0^{(r)} + \mathcal{A}^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathsf{B}_{n_r}\right) + \left[\mathcal{B}^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathsf{B}_{n_r}\right) - \kappa^{(r)} - \mathsf{u}\mathbf{e}_c\right]'\, w_t\right\}
\end{aligned}
$$

Applying the same logic to the remaining terms, and assuming default has not occurred at date t, we obtain the result of Equation (Equation 3.22):

$$
\begin{aligned}
B_t^{(n)} \; = \; & \lim_{\mathsf{u}\to+\infty} e^{\mathsf{A}_{n_r} - \kappa^{(r)\prime} w_t} \sum_{i=1}^{n} e^{-i\kappa_0^{(r)}}\left[\exp\left\{\mathcal{A}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathsf{B}_{n_r}\right) + \mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathsf{B}_{n_r}\right)' w_t\right\}\right. \\
& - \left.\exp\left\{\mathcal{A}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathsf{B}_{n_r} - \mathsf{u}\mathbf{e}_c\right) + \mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathsf{B}_{n_r} - \mathsf{u}\mathbf{e}_c\right)' w_t\right\}\right] \\
& + \exp\left\{-n\kappa_0^{(r)} + \mathcal{A}_n^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, -\mathsf{u}\mathbf{e}_c\right) + \left[\mathcal{B}_n^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, -\mathsf{u}\mathbf{e}_c\right) - \kappa^{(r)}\right]' w_t\right\} ,
\end{aligned}
$$

Let us now turn to TIPS valuation. Again, for convenience, we rewrite the general pricing formula given by Equation (Equation 3.21) below:

$$
\begin{aligned}
B_t^{*^{(n)}} &= \sum_{i=1}^{n} \mathbb{E}_t^{\mathbb{Q}} \left[\exp\left(-\sum_{j=0}^{i-1} r_{t+j} - \rho^* \pi_{t+j+1} \right) \mathcal{P}_{t+i}^{(n_r)} \times \left(\mathbb{1}\left\{ \sum_{j=0}^{i-1} \delta_{t+j}^{(c)} = 0 \right\} - \mathbb{1}\left\{ \sum_{j=0}^{i} \delta_{t+j}^{(c)} = 0 \right\} \right) \right] \\
+ & \quad \mathbb{E}_t^{\mathbb{Q}} \left[\exp\left(-\sum_{j=0}^{i-1} r_{t+j} - \pi_{t+j+1} \right) e^{-\delta_{t+i}^{(\ell)}} \times \mathbb{1}\left\{ \sum_{j=0}^{i} \delta_{t+j}^{(c)} = 0 \right\} \left(\mathbb{1}\left\{ \sum_{j=0}^{i-1} \delta_{t+j}^{(\ell)} = 0 \right\} - \mathbb{1}\left\{ \sum_{j=0}^{i} \delta_{t+j}^{(\ell)} = 0 \right\} \right) \right] \\
+ & \quad \mathbb{E}_t^{\mathbb{Q}} \left[\exp\left(-\sum_{j=0}^{n-1} r_{t+j} - \pi_{t+j+1} \right) \mathbb{1}\left\{ \sum_{j=0}^{n} \delta_{t+j}^{(c)} = 0 \right\} \mathbb{1}\left\{ \sum_{j=0}^{n} \delta_{t+j}^{(\ell)} = 0 \right\} \right] .
\end{aligned}
$$

Let us first justify these different terms. The first row corresponds to the expected discounted ($e^{-r_t - \ldots - r_{t+i-1}}$) recovery cashflow ($e^{\rho^*(\pi_{t+1}+\ldots+\pi_{t+i})}\mathcal{P}_{t+i}^{(n_r)}$) in case default happens at date $t+i$ exactly (difference of indicators). The second row is the expected discounted ($e^{-r_t - \ldots - r_{t+i-1}}$) liquidity recovery cashflow (recovery rate $e^{-\delta_{t+i}^{(\ell)}}$ on face value $e^{\pi_{t+1}+\ldots+\pi_{t+i}}$) if no default has happened and liquidity event happens exactly at $t+i$. The last row is the expected discounted inflated face value if no credit or liquidity events have happened. In terms of asset pricing, assuming no default at date t, the first term of this equation can be detailed as:

$$
\begin{aligned}
& \mathbb{E}_t^{\mathbb{Q}} \left[\exp\left(-\sum_{j=0}^{i-1} r_{t+j} - \rho^* \pi_{t+j+1} \right) \mathcal{P}_{t+i}^{(n_r)} \times \mathbb{1}\left\{ \sum_{j=0}^{i-1} \delta_{t+j}^{(c)} = 0 \right\} \right] \\
= & \lim_{\mathsf{u} \to +\infty} e^{-i\left(\kappa_0^{(r)} - \rho^* \kappa_0^{(\pi)}\right) + \mathsf{A}_{\mathsf{n_r}} - \kappa^{(r)\prime} w_t} \\
& \mathbb{E}_t^{\mathbb{Q}} \left[\exp\left(-\sum_{j=1}^{i-1} \left(\kappa^{(r)} - \rho^* \kappa^{(\pi)} + \mathsf{u}\mathbf{e}_c \right)' w_{t+j} + \left(\mathsf{B}_{n_r} + \kappa^{(\pi)} \right)' w_{t+1} \right) \right] \\
= & \lim_{\mathsf{u} \to +\infty} \exp\Big\{ -i\left(\kappa_0^{(r)} - \rho^* \kappa_0^{(\pi)} \right) + \mathsf{A}_{\mathsf{n_r}} + \mathcal{A}_i^{\mathbb{Q}}\left(\rho^* \kappa^{(\pi)} - \kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\ \rho^* \kappa^{(\pi)} + \mathsf{B}_{n_r} \right) \\
& \quad + \quad \left[\mathcal{B}_i^{\mathbb{Q}}\left(\rho^* \kappa^{(\pi)} - \kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\ \rho^* \kappa^{(\pi)} + \mathsf{B}_{n_r} \right) - \kappa^{(r)} \right]' w_t \Big\} .
\end{aligned}
$$

Using the same properties, we obtain:

$$
\begin{aligned}
& \mathbb{E}_t^{\mathbb{Q}}\left[\exp\left(-\sum_{j=0}^{i-1} r_{t+j} - \rho^* \pi_{t+j+1}\right) \mathcal{P}_{t+i}^{(n_r)} \times \mathbb{1}\left\{\sum_{j=0}^{i} \delta_{t+j}^{(c)} = 0\right\}\right] \\
= & \lim_{\mathsf{u}\to+\infty} \exp\left\{-i\left(\kappa_0^{(r)} - \rho^* \kappa_0^{(\pi)}\right) + \mathsf{A}_{\mathsf{n_r}} + \mathcal{A}_i^{\mathbb{Q}}\left(\rho^* \kappa^{(\pi)} - \kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\ \rho^* \kappa^{(\pi)} + \mathsf{B}_{n_r} - \mathsf{u}\mathbf{e}_c\right)\right. \\
+ & \left.\left[\mathcal{B}_i^{\mathbb{Q}}\left(\rho^* \kappa^{(\pi)} - \kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\ \rho^* \kappa^{(\pi)} + \mathsf{B}_{n_r} - \mathsf{u}\mathbf{e}_c\right) - \kappa^{(r)}\right]' w_t\right\},
\end{aligned}
$$

$$
\begin{aligned}
& \mathbb{E}_t^{\mathbb{Q}}\left[\exp\left(-\sum_{j=0}^{i-1} r_{t+j} - \pi_{t+j+1}\right) e^{-\delta_{t+i}^{(\ell)}} \times \mathbb{1}\left\{\sum_{j=0}^{i} \delta_{t+j}^{(c)} = 0\right\} \mathbb{1}\left\{\sum_{j=0}^{i-1} \delta_{t+j}^{(\ell)} = 0\right\}\right] \\
= & \lim_{\mathsf{u}\to+\infty} \exp\left\{-i\left(\kappa_0^{(r)} - \kappa_0^{(\pi)}\right) + \mathcal{A}_i^{\mathbb{Q}}\left(\kappa^{(\pi)} - \kappa^{(r)} - \mathsf{u}\mathbf{e}_c - \mathsf{u}\mathbf{e}_\ell,\ \kappa^{(\pi)} - \mathsf{u}\mathbf{e}_c - \mathbf{e}_\ell\right)\right. \\
+ & \left.\left[\mathcal{B}_i^{\mathbb{Q}}\left(\kappa^{(\pi)} - \kappa^{(r)} - \mathsf{u}\mathbf{e}_c - \mathsf{u}\mathbf{e}_\ell,\ \kappa^{(\pi)} - \mathsf{u}\mathbf{e}_c - \mathbf{e}_\ell\right) - \kappa^{(r)}\right]' w_t\right\},
\end{aligned}
$$

and

$$
\begin{aligned}
& \mathbb{E}_t^{\mathbb{Q}}\left[\exp\left(-\sum_{j=0}^{i-1} r_{t+j} - \pi_{t+j+1}\right) e^{-\delta_{t+i}^{(\ell)}} \times \mathbb{1}\left\{\sum_{j=0}^{i} \delta_{t+j}^{(c)} = 0\right\} \mathbb{1}\left\{\sum_{j=0}^{i} \delta_{t+j}^{(\ell)} = 0\right\}\right] \\
= & \lim_{\mathsf{u}\to+\infty} \exp\left\{-i\left(\kappa_0^{(r)} - \kappa_0^{(\pi)}\right) + \mathcal{A}_i^{\mathbb{Q}}\left(\kappa^{(\pi)} - \kappa^{(r)} - \mathsf{u}\mathbf{e}_c - \mathsf{u}\mathbf{e}_\ell,\ \kappa^{(\pi)} - \mathsf{u}\mathbf{e}_c - \mathsf{u}\mathbf{e}_\ell\right)\right. \\
+ & \left.\left[\mathcal{B}_i^{\mathbb{Q}}\left(\kappa^{(\pi)} - \kappa^{(r)} - \mathsf{u}\mathbf{e}_c - \mathsf{u}\mathbf{e}_\ell,\ \kappa^{(\pi)} - \mathsf{u}\mathbf{e}_c - \mathsf{u}\mathbf{e}_\ell\right) - \kappa^{(r)}\right]' w_t\right\},
\end{aligned}
$$

which is also the last term when $i = n$. Putting all these terms together, we obtain the result of Equation (Equation 3.23).

C.1.7 Pricing formulas for CDS spreads

The protection seller and protection buyer values are respectively given by:

$$
\mathrm{PS}_t^{(n)} = \sum_{i=1}^{n} \mathbb{E}_t^{\mathbb{Q}}\left[\exp\left(-\sum_{j=0}^{i-1} r_{t+j}\right)\left(1 - \mathcal{P}_{t+i}^{(n_r)}\right)\left(\mathbb{1}\left\{\sum_{j=0}^{i-1} \delta_{t+j}^{(c)} = 0\right\} - \mathbb{1}\left\{\sum_{j=0}^{i} \delta_{t+j}^{(c)} = 0\right\}\right)\right],
$$

and

$$\mathrm{PB}_t^{(n)} = \mathcal{S}_t^{(n)} \sum_{i=1}^{n} \mathbb{E}_t^{\mathbb{Q}} \left[\exp\left(-\sum_{j=0}^{i-1} r_{t+j} \right) \mathbb{1}\left\{ \sum_{j=0}^{i} \delta_{t+j}^{(c)} = 0 \right\} \right]$$

Applying the same pricing principle as in Appendix subsection C.1.6, we can easily express the protection buyer value as:

$$\begin{aligned}
& \mathcal{S}_t^{(n)} \sum_{i=1}^{n} \mathbb{E}_t^{\mathbb{Q}} \left[\exp\left(-\sum_{j=0}^{i-1} r_{t+j} \right) \mathbb{1}\left\{ \sum_{j=0}^{i} \delta_{t+j}^{(c)} = 0 \right\} \right] \\
= & \lim_{\mathsf{u}\to+\infty} \mathcal{S}_t^{(n)} \sum_{i=1}^{n} e^{-i\kappa_0^{(r)} - \kappa^{(r)\prime} w_t} \mathbb{E}_t^{\mathbb{Q}} \left[\exp\left(-\sum_{j=0}^{i-1} \left(\kappa^{(r)} + \mathsf{u}\mathbf{e}_c \right)' w_{t+j} - \mathsf{u}\mathbf{e}_c' w_{t+i} \right) \right] \\
= & \lim_{\mathsf{u}\to+\infty} \mathcal{S}_t^{(n)} e^{-\kappa^{(r)\prime} w_t} \sum_{i=1}^{n} \exp\left\{ -i\kappa_0^{(r)} + \mathcal{A}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c, -\mathsf{u}\mathbf{e}_c \right) + \mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c, -\mathsf{u}\mathbf{e}_c \right)' w_t \right\}
\end{aligned}$$

For the protection seller leg, we can separate the term in $(1 - \mathcal{P}_{t+i}^{(n_r)}$ in two and treat these two terms. The first term,

$$\sum_{i=1}^{n} \mathbb{E}_t^{\mathbb{Q}} \left[\exp\left(-\sum_{j=0}^{i-1} r_{t+j} \right) \left(\mathbb{1}\left\{ \sum_{j=0}^{i-1} \delta_{t+j}^{(c)} = 0 \right\} - \mathbb{1}\left\{ \sum_{j=0}^{i} \delta_{t+j}^{(c)} = 0 \right\} \right) \right],$$

would be the price of a nominal treasury with recovery payment of the full face value, forgetting the principal repayment at maturity provided no default has happened (the last term of Equation (Equation 3.20) is missing). The second term,

$$\sum_{i=1}^{n} \mathbb{E}_t^{\mathbb{Q}} \left[\exp\left(-\sum_{j=0}^{i-1} r_{t+j} \right) \mathcal{P}_{t+i}^{(n_r)} \left(\mathbb{1}\left\{ \sum_{j=0}^{i-1} \delta_{t+j}^{(c)} = 0 \right\} - \mathbb{1}\left\{ \sum_{j=0}^{i} \delta_{t+j}^{(c)} = 0 \right\} \right) \right],$$

is exactly the first row of Equation (Equation 3.20), so it is the price of a nominal treasury, forgetting the principal repayment at maturity provided no default has happened. In the end, taking the difference between these two terms, it is innocuous to add the discounted value of the last payment in both terms since they are canceling out in the difference. We hence obtain that the protection seller value is the difference between the price of a nominal treasury with recovery payment of $1 and the price of the standard nominal treasury. The result of Equation (Equation 3.25) is obtained by equation the protection buyer and seller values.

C.1.8 Gradient computation for measurement equations

We use the extended Kalman filter for estimation, which requires the computation of the gradient of the pricing equations in the factors. Since our pricing equations are closed-form, we have closed-form gradients as well. Since these computations are the result of tedious algebra, we only present the results without justification.

Let us start with riskless yields. Given the formulation of $D_t^{(n)}$ and $D_t^{*(n)}$ of Equation (Equation 3.17), and denoting by $r_t^{(n)} = -n^{-1}\log D_t^{(n)}$ and $r_t^{*(n)} = -n^{-1}\log D_t^{*(n)}$, we trivially have:

$$
\begin{aligned}
\frac{\partial\, r_t^{(n)}}{\partial\, w_t} &= \frac{\kappa^{(r)} - \mathcal{B}_n^{\mathbb{Q}}\left(-\kappa^{(r)}, \mathbf{0}\right)}{n} \\
\frac{\partial\, r_t^{*(n)}}{\partial\, w_t} &= \frac{\kappa^{(r)} - \mathcal{B}_n^{\mathbb{Q}}\left(\kappa^{(\pi)} - \kappa^{(r)}, \kappa^{(\pi)}\right)}{n}\,.
\end{aligned}
$$

Let us turn now to nominal treasuries and TIPS. Continuously compounded yields of these bonds are respectively denoted by $R_t^{(n)} = -n^{-1}\log B_t^{(n)}$ and $R_t^{*(n)} = -n^{-1}\log B_t^{*(n)}$. It is useful to define the differentials with respect to the price instead of the yield directly. Using the chain rule, we have:

$$
\begin{aligned}
\frac{\partial\, R_t^{(n)}}{\partial\, w_t} &= -\frac{1}{n} \times \frac{\partial\, B_t^{(n)}}{\partial\, w_t} \times \frac{1}{B_t^{(n)}} \\
\frac{\partial\, R_t^{*(n)}}{\partial\, w_t} &= -\frac{1}{n} \times \frac{\partial\, B_t^{*(n)}}{\partial\, w_t} \times \frac{1}{B_t^{*(n)}}\,.
\end{aligned}
$$

Let us focus on the differential of the nominal bond price first.

$$
\begin{aligned}
\frac{\partial B_t^{(n)}}{\partial w_t} = \lim_{\mathsf{u}\to+\infty} e^{\mathsf{A}_{n_r}} \sum_{i=1}^{n} e^{-i\kappa_0^{(r)}} \Bigg[& \\
& \exp\left\{\mathcal{A}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathsf{B}_{n_r}\right) + \left[\mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathsf{B}_{n_r}\right) - \kappa^{(r)}\right]' w_t\right\} \\
& \times \left[\mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathsf{B}_{n_r}\right) - \kappa^{(r)}\right] \\
- \quad & \exp\left\{\mathcal{A}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathsf{B}_{n_r} - \mathsf{u}\mathbf{e}_c\right) + \left[\mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathsf{B}_{n_r} - \mathsf{u}\mathbf{e}_c\right) - \kappa^{(r)}\right]' w_t\right\} \\
& \times \left[\mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathsf{B}_{n_r} - \mathsf{u}\mathbf{e}_c\right) - \kappa^{(r)}\right] \Bigg] \\
+ \quad & \exp\left\{-n\kappa_0^{(r)} + \mathcal{A}_n^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, -\mathsf{u}\mathbf{e}_c\right) + \left[\mathcal{B}_n^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, -\mathsf{u}\mathbf{e}_c\right) - \kappa^{(r)}\right]' w_t\right\} \\
& \times \left[\mathcal{B}_n^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, -\mathsf{u}\mathbf{e}_c\right) - \kappa^{(r)}\right] .
\end{aligned}
$$

For TIPS, applying a similar principle:

$$
\begin{aligned}
\frac{\partial B_t^{*(n)}}{\partial w_t} = \lim_{\mathsf{u}\to+\infty} \quad & e^{\mathsf{A}_{n_r}} \sum_{i=1}^{n} e^{-i\left(\kappa_0^{(r)}-\rho^*\kappa_0^{(\pi)}\right)} \Bigg[\exp\Big\{ \mathcal{A}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c + \rho^*\kappa^{(\pi)},\, \mathsf{B}_{n_r} + \rho^*\kappa^{(\pi)}\right) \\
& + \left[\mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c + \rho^*\kappa^{(\pi)},\, \mathsf{B}_{n_r} + \rho^*\kappa^{(\pi)}\right) - \kappa^{(r)}\right]' w_t \Big\} \\
& \times \left[\mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c + \rho^*\kappa^{(\pi)},\, \mathsf{B}_{n_r} + \rho^*\kappa^{(\pi)}\right) - \kappa^{(r)}\right] \\
- \quad & \exp\Big\{ \mathcal{A}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c + \rho^*\kappa^{(\pi)},\, \mathsf{B}_{n_r} - \mathsf{u}\mathbf{e}_c + \rho^*\kappa^{(\pi)}\right) \\
& + \left[\mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c + \rho^*\kappa^{(\pi)},\, \mathsf{B}_{n_r} - \mathsf{u}\mathbf{e}_c + \rho^*\kappa^{(\pi)}\right) - \kappa^{(r)}\right]' w_t \Big\} \\
& \times \left[\mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c + \rho^*\kappa^{(\pi)},\, \mathsf{B}_{n_r} - \mathsf{u}\mathbf{e}_c + \rho^*\kappa^{(\pi)}\right) - \kappa^{(r)}\right] \Bigg] \\
+ \quad & \sum_{i=1}^{n} e^{-i\left(\kappa_0^{(r)}-\kappa_0^{(\pi)}\right)} \Bigg[\exp\Big\{ \mathcal{A}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c - \mathsf{u}\mathbf{e}_\ell + \kappa^{(\pi)},\, -\mathsf{u}\mathbf{e}_c - \mathbf{e}_\ell + \kappa^{(\pi)}\right) \\
& + \left[\mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c - \mathsf{u}\mathbf{e}_\ell + \kappa^{(\pi)},\, -\mathsf{u}\mathbf{e}_c - \mathbf{e}_\ell + \kappa^{(\pi)}\right) - \kappa^{(r)}\right]' w_t \Big\} \\
& \times \left[\mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c - \mathsf{u}\mathbf{e}_\ell + \kappa^{(\pi)},\, -\mathsf{u}\mathbf{e}_c - \mathbf{e}_\ell + \kappa^{(\pi)}\right) - \kappa^{(r)}\right] \\
- \quad & \exp\Big\{ \mathcal{A}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c - \mathsf{u}\mathbf{e}_\ell + \kappa^{(\pi)},\, -\mathsf{u}\mathbf{e}_c - \mathsf{u}\mathbf{e}_\ell + \kappa^{(\pi)}\right) \\
& + \left[\mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c - \mathsf{u}\mathbf{e}_\ell + \kappa^{(\pi)},\, -\mathsf{u}\mathbf{e}_c - \mathsf{u}\mathbf{e}_\ell + \kappa^{(\pi)}\right) - \kappa^{(r)}\right]' w_t \Big\} \\
& \times \left[\mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c - \mathsf{u}\mathbf{e}_\ell + \kappa^{(\pi)},\, -\mathsf{u}\mathbf{e}_c - \mathsf{u}\mathbf{e}_\ell + \kappa^{(\pi)}\right) - \kappa^{(r)}\right] \Bigg] \\
+ \quad & \exp\Big\{ -n\left(\kappa_0^{(r)} - \kappa_0^{(\pi)}\right) + \mathcal{A}_n^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c - \mathsf{u}\mathbf{e}_\ell + \kappa^{(\pi)},\, -\mathsf{u}\mathbf{e}_c - \mathsf{u}\mathbf{e}_\ell + \kappa^{(\pi)}\right) \\
& + \left[\mathcal{B}_n^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c - \mathsf{u}\mathbf{e}_\ell + \kappa^{(\pi)},\, -\mathsf{u}\mathbf{e}_c - \mathsf{u}\mathbf{e}_\ell + \kappa^{(\pi)}\right) - \kappa^{(r)}\right]' w_t \Big\} \\
& \times \left[\mathcal{B}_n^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c - \mathsf{u}\mathbf{e}_\ell + \kappa^{(\pi)},\, -\mathsf{u}\mathbf{e}_c - \mathsf{u}\mathbf{e}_\ell + \kappa^{(\pi)}\right) - \kappa^{(r)}\right].
\end{aligned}
$$

Last, for the CDS, let us denote by:

$$\mathcal{S}_t^{(n)} = \frac{f_n(w_t)}{g_n(w_t)},$$

where $f_n(\bullet)$ and $g_n(\bullet)$ are explicit functions given by Equation (Equation 3.25). Using differentiation rules:

$$\frac{\partial\, \mathcal{S}_t^{(n)}}{\partial\, w_t} = \frac{1}{g_n(w_t)} \times \frac{\partial\, f_n(w_t)}{\partial\, w_t} - \frac{f_n(w_t)}{g_n(w_t)^2} \times \frac{\partial\, g_n(w_t)}{\partial\, w_t}.$$

The differential of $f_n(w_t)$ is easily obtained as a function of the differential of nominal treasuries:

$$
\begin{aligned}
\frac{\partial f_n(w_t)}{\partial w_t} = \lim_{\mathsf{u}\to+\infty} \sum_{i=1}^{n} e^{-i\kappa_0^{(r)}} \Bigg[\\
& \exp\left\{\mathcal{A}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathbf{0}\right) + \left[\mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathbf{0}\right) - \kappa^{(r)}\right]' w_t\right\} \\
& \times \left[\mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathbf{0}\right) - \kappa^{(r)}\right] \\
- \quad & \exp\left\{\mathcal{A}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, -\mathsf{u}\mathbf{e}_c\right) + \left[\mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, -\mathsf{u}\mathbf{e}_c\right) - \kappa^{(r)}\right]' w_t\right\} \\
& \times \left[\mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, -\mathsf{u}\mathbf{e}_c\right) - \kappa^{(r)}\right] \\
- \quad & \exp\left\{\mathsf{A}_{n_r} + \mathcal{A}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathsf{B}_{n_r}\right) + \left[\mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathsf{B}_{n_r}\right) - \kappa^{(r)}\right]' w_t\right\} \\
& \times \left[\mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathsf{B}_{n_r}\right) - \kappa^{(r)}\right] \\
+ \quad & \exp\left\{\mathsf{A}_{n_r} + \mathcal{A}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathsf{B}_{n_r} - \mathsf{u}\mathbf{e}_c\right) + \left[\mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathsf{B}_{n_r} - \mathsf{u}\mathbf{e}_c\right) - \kappa^{(r)}\right]' w_t\right\} \\
& \qquad \times \quad \left[\mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, \mathsf{B}_{n_r} - \mathsf{u}\mathbf{e}_c\right) - \kappa^{(r)}\right] \Bigg],
\end{aligned}
$$

and, for the function $g_n(w_t)$:

$$
\begin{aligned}
\frac{\partial g_n(w_t)}{\partial w_t} \quad = \quad & \lim_{\mathsf{u}\to+\infty} \sum_{i=1}^{n} \Bigg(\exp\left\{-i\kappa_0^{(r)} + \mathcal{A}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, -\mathsf{u}\mathbf{e}_c\right) + \left[\mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, -\mathsf{u}\mathbf{e}_c\right) - \kappa^{(r)}\right] \\
& \qquad \times \quad \left[\mathcal{B}_i^{\mathbb{Q}}\left(-\kappa^{(r)} - \mathsf{u}\mathbf{e}_c,\, -\mathsf{u}\mathbf{e}_c\right) - \kappa^{(r)}\right] \Bigg).
\end{aligned}
$$

C.1.9 Supplementary Tables

Table C.1: **Cheapest-to-Deliver**

Table C.1 shows the results from a panel regression of ILS-BEI on US CDS spreads and various controls using daily observations. Information on the prevailing cheapest-to-deliver outstanding U.S. government nominal bond on each trading day is added as a control as set forth in [92]. The sample period is from January 2008 to October 2015. $ILS - BEI$ is the difference in the inflation swap rate and the breakeven inflation rate (Treasury-TIPS) for 2-, 3-. 5-, 7-, and 10-year tenors. $US\ CDS$ spreads are for the 5-year tenor. $HPWNoise$ follows [101]. $TIPS\ Noise$ measures average daily deviations in the real yield curve. $LIBOR - OIS$ is the difference in the London Inter-bank Offered Rate and the overnight indexed swap rate. $OTR\ Difference$ is the difference in 10-year Treasury par yield from [99] less the on-the-run 10-year Treasury yield from Bloomberg. VIX denotes the CBOE Volatility Index. Standard errors are reported in parentheses.

Dep Var: ILS-BEI Spread	(1)	(2)	(3)
US CDS	0.184***	0.217***	0.217***
	(0.050)	(0.052)	(0.052)
ILS-BEI$_{t-1}$	0.822***	0.823***	0.817***
	(0.005)	(0.005)	(0.005)
CtD	−0.134	−0.222**	−0.221**
	(0.095)	(0.099)	(0.099)
HPW Noise		0.634**	0.630**
		(0.291)	(0.290)
TIPS Noise		−1.042***	−1.036***
		(0.182)	(0.182)
LIBOR-OIS		−3.798**	−3.786**
		(1.925)	(1.922)
OTR Difference		−17.962***	−18.021***
		(5.091)	(5.082)
VIX		−0.049	−0.048
		(0.043)	(0.042)
Week	Yes	Yes	Yes
Tenor	No	No	Yes
Observations	9147	9127	9127
R^2	0.149	0.155	0.159

*,**,*** represent statistical significance at the 10%, 5%, and 1% critical threshold, respectively.

Table C.2: **Controlling for Foreign Exchange Risk**

Table C.2 shows the results from a panel regression of $ILS - BEI$ on US CDS spreads and specifically controls for Euro-Dollar exchange rate movement using daily observations. The sample period is from January 2008 to October 2015. $US\ CDS$ spreads are for the 5-year tenor. $EURUSD$ denotes the 5-year swap spread of the Euro-Dollar basis swap. $Spot$ is the spot exchange rate between the Euro and the Dollar. $HPWNoise$ follows [101]. $TIPS\ Noise$ measures average daily deviations in the real yield curve. $LIBOR - OIS$ is the difference in the London Inter-bank Offered Rate and the overnight indexed swap rate. $OTR\ Difference$ is the difference in 10-year Treasury par yield from [99] less the on-the-run 10-year Treasury yield from Bloomberg. VIX denotes the CBOE Volatility Index. Standard errors are reported in parentheses.

Dep Var: ILS-BEI Spread	(1)	(2)	(3)	(4)
US CDS	0.178***	0.208***	0.213***	0.237***
	(0.051)	(0.050)	(0.052)	(0.052)
ILS-BEI$_{t-1}$	0.816***	0.817***	0.817***	0.817***
	(0.005)	(0.005)	(0.005)	(0.005)
EURUSD	–0.076		–0.091*	
	(0.051)		(0.053)	
Spot		10.352		11.461
		(8.067)		(8.313)
HPW Noise			0.611**	0.649**
			(0.291)	(0.291)
TIPS Noise			–1.027***	–1.044***
			(0.182)	(0.182)
LIBOR-OIS			–3.881**	–4.145**
			(1.921)	(1.926)
OTR Difference			–17.077***	–17.430***
			(5.081)	(5.076)
VIX			–0.045	–0.008
			(0.043)	(0.042)
Week	Yes	Yes	Yes	Yes
Tenor	Yes	Yes	Yes	Yes
Observations	9142	9147	9127	9127
$1 - \mathbb{V}(\varepsilon_t)/\mathbb{V}[\Delta(\mathrm{ILS}_t - \mathrm{BEI}_t)]$	0.152	0.152	0.159	0.158

*,**,*** represent statistical significance at the 10%, 5%, and 1% critical threshold, respectively.

Table C.3: **FLL Mispricing - January 2008 to October 2015**

Table C.3 shows the results from a panel regression of [66] Treasury-TIPS pairwise mispricing on US CDS spreads and various controls using daily observations. The sample period is from January 2008 to October 2015. $FLL\ Mispricing$ is the difference between the price of a Treasury bond and the price of a basket of TIPS, inflation swaps, and Treasury strips. $US\ CDS$ spreads are for the 5-year tenor. TTM denotes time-to-maturity. $HPWNoise$ follows [101]. $TIPS\ Noise$ measures average daily deviations in the real yield curve. $LIBOR-OIS$ is the difference in the London Inter-bank Offered Rate and the overnight indexed swap rate. $OTR\ Difference$ is the difference in 10-year Treasury par yield from [99] less the on-the-run 10-year Treasury yield from Bloomberg. VIX denotes the CBOE Volatility Index. Clustered standard errors by bond-pair are reported in parentheses.

Dep Var: FLL Mispricing	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
US CDS	0.665***	0.666***	0.768***	0.631***	0.686***	0.420**	0.501***	0.501***
	(0.203)	(0.203)	(0.226)	(0.187)	(0.219)	(0.172)	(0.181)	(0.180)
FLL-Mis$_{t-1}$	95.408***	95.408***	95.475***	95.411***	95.476***	95.467***	95.473***	94.340***
	(0.752)	(0.752)	(0.762)	(0.751)	(0.762)	(0.758)	(0.761)	(0.782)
TTM	0.003***	0.003***	0.003***	0.003***	0.003***	0.003***	0.003***	–0.111*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.058)
HPW Noise		–0.597					–0.527	–0.483
		(0.876)					(0.904)	(0.911)
TIPS Noise			–5.159***				–5.440***	–5.416***
			(0.728)				(0.835)	(0.834)
LIBOR-OIS				22.849			2.477	2.547
				(13.765)			(10.031)	(9.989)
OTR Difference					3.768		16.987	16.112
					(33.450)		(35.297)	(34.943)
VIX						1.186***	1.196***	1.190***
						(0.283)	(0.264)	(0.263)
Week	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Bond Pair	No	No	No	No	No	No	No	Yes
Observations	43156	43156	41466	43156	41505	41667	41357	41357
R^2	0.976	0.976	0.977	0.977	0.977	0.977	0.977	0.977

*,**,*** represent statistical significance at the 10%, 5%, and 1% critical threshold, respectively.

Table C.4: **Controlling for Repo Premium**

Table C.4 shows the results from a panel regression of $ILS - BEI$ on US CDS spreads and various controls including repo premiums [112] using daily observations. The sample period is from January 2009 to October 2015. $ILS - BEI$ is the difference in the inflation swap rate and the breakeven inflation rate (Treasury-TIPS) for 2-, 3-. 5-, 7-, and 10-year tenors. $US\ CDS$ spreads are for the 5-year tenor. $HPWNoise$ follows [101]. $TIPS\ Noise$ measures average daily deviations in the real yield curve. $LIBOR - OIS$ is the difference in the London Inter-bank Offered Rate and the overnight indexed swap rate. $OTR\ Difference$ is the difference in 10-year Treasury par yield from [99] less the on-the-run 10-year Treasury yield from Bloomberg. VIX denotes the CBOE Volatility Index. Standard errors are reported in parentheses.[]

Dep Var: ILS-BEI	(1)	(2)	(3)
US CDS	0.092**	0.078**	0.078**
	(0.037)	(0.039)	(0.038)
ILS-BEI$_{t-1}$	0.811***	0.810***	0.796***
	(0.006)	(0.006)	(0.006)
Repo Premium	3.105	5.080	4.827
	(5.185)	(5.356)	(5.328)
HPW Noise		0.358	0.353
		(0.264)	(0.263)
TIPS Noise		–0.566**	–0.554**
		(0.223)	(0.222)
LIBOR-OIS		8.056	8.514
		(5.719)	(5.689)
OTR Difference		–7.915*	–7.957*
		(4.572)	(4.548)
VIX		0.079**	0.080**
		(0.035)	(0.035)
Week	Yes	Yes	Yes
Tenor	No	No	Yes
Observations	7950	7930	7930
$1 - \mathbb{V}(\varepsilon_t)/\mathbb{V}[\Delta(\text{ILS}_t - \text{BEI}_t)]$	0.171	0.173	0.182

*,**,*** represent statistical significance at the 10%, 5%, and 1% critical threshold, respectively.

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VITA

Peter Simasek completed his Ph.D. in Finance at the Scheller College of Business, Georgia Institute of Technology. Prior to his doctoral studies, he worked in the investment banking and asset management industries. He completed his Bachelor's degree concentrating in Finance and Accounting at the McIntire School of Commerce, University of Virginia.

Peter's interests include corporate pensions, fixed income, and empirical asset pricing. His work has been presented at numerous conferences including the American Finance Association (AFA) and European Finance Association (EFA) annual meetings. In 2020, the Review of Asset Pricing Studies published his work, *COVID-19 and the Cross-Section of Equity Returns: Impact and Transmission*. He has received two teaching awards and the Ashford Watson Stalnaker Memorial Award for Ph.D. excellence.